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"Biomas Nutrient Pool, and Influence of Biomas
Burning in the Brzilian Amazon and Cerrado"
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Biomass Nutrient Pools and Influences of Biomass Burning in the Brazilian Amazon and Cerrado

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Introduction

The following final report covers interdisciplinary research conducted with scientists from Oregon State University, NASA, the US Forest Service Intermountain Experiment Station and Scientists from the Brazilian Space Agency (INPE) and the Brazilian Forest Service (IBAMA). In addition, we list some of the publications that are currently arising from this research. The list of publications is by no means complete. Additional papers are currently being prepared and will be submitted for publication in the future.

The highlights of the research include field research conducted in 1993 and 1995. Funding also including extensive data and laboratory analysis for field work conducted in 1993 and 1995. The fieldwork that was funded by this particular funding is found in chapter 2. This concerns the research results of the SCAR-B Project in which 2 slashed primary forests and one pasture was sampled for biomass, combustion factors and nutrient loss in 1995. These sites were located in Rondonia, Brazil. They are typical sites burned by small farmers. The unique aspect of this study was that for the first time we were able to calculate the biomass, consumption and elemental loss on a whole site basis. This is an important data of value for calibration in remote sensing studies. These sites were also the sites of emmsions estimated made by USFS and Brazilian scientists.

The next chapter includes the final results and discussion of an in-depth study examining the biomass of standing rainforest of Rondonia, Brazil. In this study we sampled 20 forest sites that were also sampled by the Projecto RADAMBRASIL in the early 1970's. The RADAMBRASIL inventory has been suggested to be of value to calculate the biomass and C pools of the Amazon Basin in its entirety. Yet we know of no quantitative attempt to test the hypothesis that biomass can be accurately estimated from forest inventory (volume data). In this study we found that total aboveground biomass ranged from 298-533 Mg/ha. This is similar to the studies of slash burned forest sites that we have sampled with the USFS fire chemistry research team in Brazil since 1990 (including the results from the SCAR-B study, chapter 2).

Dynamics associated with total aboveground biomass, C, nutrient pools, and biomass burning of primary forest and pasture in Rondônia, Brazil during SCAR-B

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Abstract. Burning of slashed tropical forests and pastures is among the most significant global sources of atmospheric emissions, yet the composition of the fuels and fires that creates these emissions is not well characterized. As part of the Smoke, Clouds, and Radiation-Brazil (SCAR-B) experiment, we measured total aboveground biomass (TAGB) as well as carbon, nitrogen, and sulfur pools in one cattle pasture and two slashed primary forests in Rondônia, Brazil. These pools were measured before and immediately after fires. From these data, we calculated the quantities of biomass and elements lost to the atmosphere during biomass burning. Prefire biomass in the pasture was 66 Mg ha^{-1}; fire consumed 31% of this mass. Woody debris from the forest that occupied this site 12 years previously comprised 81% of the pasture prefire TAGB. Elemental inputs into the atmosphere (site losses) from the pasture fire were 9 Mg C ha^{-1}, 88 kg N ha^{-1}, and 5 kg S ha^{-1}. Combining previous studies with this one, we calculate that the mean TAGB of Amazonian pastures is 74 Mg ha^{-1} with a mean combustion factor of 46%. Mean nutrient losses from pasture fires in Amazonia are 14 Mg C ha^{-1}, 199 kg N ha^{-1}, and 16 kg S ha^{-1}. The TAGB of the two slashed primary forests before fire was 355 and 399 Mg ha^{-1} and following fire was 188 and 185 Mg ha^{-1} (i.e., a combustion factor of 47 and 54%), respectively. Combining this study with other studies of Amazon slashed primary forests, we calculate that the mean TAGB is 349 Mg ha^{-1} and the mean combustion factor is 48%. Total elemental losses arising from the primary forest slash fires in this study were notably higher than losses from the pasture site: 79 and 102 Mg C ha^{-1}; 1019 and 1196 kg N ha^{-1}; and 87 and 96 kg S ha^{-1}. From this study combined with previous research in Rondônia and Pará, we calculate that mean nutrient losses from primary forest slash fires are 88 Mg C ha^{-1}, 1181 kg N ha^{-1}, and 107 kg S ha^{-1}. As rates of deforestation are remaining high in the Brazilian Amazon and pastures are the most frequent end product, it can be expected that these will remain the dominant sources of atmospheric emissions from Amazonia in the future.

1. Introduction

An estimated 400,000 km^2 of the Brazilian Amazon forest had been cleared by 1991 [*Fearnside*, 1992; *Skole and Tucker*, 1993]. Amazon deforestation and land conversion are a consequence of complex social pressures driven by human population expansion, the state of national and global economies, foreign debt, land speculation, tax incentives, colonization, and sociopolitical forces [*Hecht and Cockburn*, 1990; *Dale et al.*, 1994; *Jones et al.*, 1995]. Annual

rates of Amazonian deforestation have been estimated to range from 15,000 km^2 [*Skole and Tucker*, 1993] to 22,000 km^2 [*Fearnside*, 1992] between 1978 and 1988, and from 11,000-19,000 km^2 yr^{-1} since that time [*Fearnside*, 1992]. While annual rates of deforestation in Amazonia have decreased for a few years following 1989, they remain high and currently may be increasing in regions such as Rondônia [*Fearnside*, 1992; *Skole and Tucker*, 1993].

Currently, the contribution of CO_2-equivalent carbon from deforestation in Brazil accounts for one-fifth of that released by global tropical deforestation [*Fearnside*, 1992]. As of 1990, however, only ≈10% of Amazonia forest had been deforested. The implications of the potential deforestation of the remaining 90% of Brazil's Amazon forest cause concern for its inevitable impact on global climate, hydrological, biogeochemical, and ecosystem processes [*Andreae et al.*, 1988; *Crutzen and Andreae*, 1990; *Dale and Pedlowski*, 1992; *Hecht and Cockburn*, 1990; *Salati*, 1987].

Deforestation and anthropogenic burning of primary forest associated with land use change in the Brazilian Amazon decrease the pools of terrestrial carbon and nutrients, and are sources of regional air pollution. Biomass burning is customarily used to convert tropical forests to shifting agriculture, permanent agriculture, and/or cattle pasture. Repeated pasture burning following conversion has been suggested to be a considerable source of carbon and other emissions to the atmosphere [*Kauffman et al.*, 1998]. Few studies have quantified carbon and nutrient dynamics associated with land conversion to agriculture in the Amazon [*Fearnside*, 1990; *Kauffman et al.*, 1995, 1998; *Uhl et al.*, 1988]. Data on losses associated with biomass burning are particularly limiting. This is important because such losses are sources of a substantial quantity of greenhouse emissions and other radiatively active gasses and aerosols [*Andreae et al.*, 1991, 1990; *Crutzen and Andreae*, 1990].

As part of the Smoke, Clouds, and Radiation-Brazil (SCAR-B) experiment, we sampled the total aboveground biomass (TAGB), elemental pools, and the subsequent losses and redistribution associated with biomass burning of two slashed primary forests and one cattle pasture. These sites were the same sites sampled for trace gas flux from the ground by *Ward et al.* [1996] and *Babbitt et al.* [1996], and monitored for fire mapping by multispectral data by *Prins et al.* [1996](see also this issue). The objectives of this study were to quantify the prefire biomass and nutrient pools and the quantity of biomass and carbon, nitrogen, and sulfur lost to the atmosphere by these fires. These data would be especially valuable in the quantification of emissions and nutrient losses arising from biomass burning at both local and regional scales.

2. Materials and Methods

2.1. Study Area

The study areas were located on small farms representative of much of the land use in Rondônia, Brazil. We obtained permission from subsistence landowners to conduct our studies prior to, during, and following the pasture and slash fires they had initiated. All decisions on the timing of slashing and burning were solely determined by the landowner. This minimized potential influences of scientists on the representativeness of these burns. Prior to our arrival, both of the primary forest sites had already been slashed. These sites were selected because the proposed burn times met the constraints of time required between equipment setup and overflights by this and related studies in this special issue.

The study areas were located approximately 100 km southeast of Porto Velho, near the small town of Jamarí and the Floresta Nacional do Jamarí, Rondônia. The pasture, owned by Jose, will be referred to in this paper as the pasture site. The pasture site was 6.9 ha in size. The two primary forest sites belonging to Balteke and Sergipe will be referred to as the Balteke and Sergipe primary forests. The Balteke and Sergipe primary forest sites were 1.5 and 3.4 ha in size, respectively. Global Positioning System (GPS) coordinates for the three sites are as follows: the cattle pasture: 9°10'42.6"S, 63°10'03"W; Balteke primary forest: 9°11'48.6"S, 63°07'22"W; and Sergipe primary forest: 9°11'49.0"S, 63°07'22"W. The forest types are classified as floresta ombrófila aberta submontana (submontane open forest) [*Instituto Brasileiro de Desenvolvimento Florestal (IBDF) and Instituto Brasileiro de Geographia e Estatistica (IBGE)*, 1993]. The soil types in the area include red-yellow podzolic latosols and red-yellow latosols [*Neill et al.*, 1997].

Climatological data were acquired from the Porto Velho, Rondônia station. Mean average precipitation is 2354 mm annually [*Departmento Nacional de Meteorologia, Brasil*, 1992]. The dry season persists between June and September with typical precipitation <100 mm per month. The mean average temperature during these months is 25.2°C with minimum and maximum temperatures of 20.9°C and 31.1°C, respectively. The mean relative humidity is 85%.

The most common land uses throughout the Amazon are logging and direct conversion of primary forest to cattle pasture or shifting cultivation [*Fearnside*, 1987](Figure 1). Based upon interviews with farmers, we have found that under shifting cultivation scenarios, crops will be grown for 2-3 years followed by a 4-6 year fallow period. During the fallow period, sites will be dominated by regenerating forests. On small land holdings, such as those

studied here, this crop/fallow sequence will usually occur twice; most landowners will convert the land to pasture when third-growth forests are cut and burned. This was the land use history of the pasture sampled in this study. Often, particularly on large land holdings, the primary forest will be cut, burned, and directly converted to pasture. Following conversion, pastures are typically burned every 2-3 years for the first 10 years of the pasture's existence; accidental fires are also very common [*Uhl and Buschbacher*, 1985; *Kauffman et al.*, 1998].

The pasture site had been originally cut and burned 12 years prior to this study (1983). The 1995 burn reported here was the first pasture fire on the site, but the fourth anthropogenic burn since 1983. The pasture site was ignited on September 2, 1995.

Both of the primary forest sites in this study area were cleared with the intention of conversion to shifting cultivation. The forest sites were cut at the beginning of the dry season, as is typical of the region for this type of land conversion in the Amazon [*Kauffman et al.*, 1995]. The understory was cleared using hand tools, and large trees and woody vines were then cut with chainsaws. Cut trees that did not fall were left standing and often fell during the burn. Following deforestation, the slash was left to dry for approximately 2 to 3 months before burning late in the dry season. The Balteke and Sergipe primary forest slash sites were ignited on September 4 and 6, 1995, respectively. Fires were ignited in the early afternoon during conditions of lowest daily humidity and highest temperatures (Table 1).

2.2. Fire and Fuel Conditions

We measured the fuel moisture content, air temperature, and relative humidity at each site prior to the burn event. Flame length was estimated during burning. Moisture content on a dry weight basis was measured on 5 - 10 samples of each of the following components: soil surface, litter, dead grass, live grass, dicots, attached foliage, and wood in diameter classes where applicable (i.e., 0.0 – 0.64 cm, 0.65 - 2.54 cm, 2.55 – 7.62 cm, and ≥ 7.63 cm diameter). Samples were weighed in the field, then oven dried at 60°C for 2-3 days to calculate oven dry weight. Air temperature and relative humidity were measured using a sling psychrometer.

2.3. Biomass

Biomass measurements closely those of *Kauffman et al.* [1995, 1998]. Pasture and primary forest slash components were partitioned based on their influence on fire behavior, nutrient composition, and plant morphology. In the pasture, TAGB was partitioned into the following components: grass, dicot seedlings, fine woody debris (< 7.63 cm in diameter), coarse woody debris (≥ 7.63 cm diameter), and ash. In the primary forest, biomass components included litter, dicot seedlings and resprouts, rootmat, attached foliage, fine and coarse woody debris, and ash. Coarse woody debris was further delineated as sound and rotten debris.

At each of the sites, 32 transects (eight clusters of four planar transects) to measure biomass were systematically established in a manner to ensure spatial distribution of sampling through the areas. Biomass of wood debris was nondestructively measured before and after burning using the planar intersect technique [*Van Wagner*, 1968]. Models were developed using specific fuel diameter and wood density data collected from the site prior to burning following approaches outlined by *Van Wagner* [1968] and *Brown and Roussopoulous* [1974]. The pasture transects were 15 m in length, and the primary forest site transects were 11 m. Aluminum stakes marked all transects prior to burning and ensured exact relocation for postfire measurements. Wood debris was partitioned into standardized diameter size classes. The diameter classes were 0 - 0.64 cm, 0.65 - 2.54 cm, 2.55 - 7.62 cm, 7.63 - 20.5 cm (sound and rotten), and > 20.5 cm (sound and rotten). Wood debris diameter is a good predictor of the rate of moisture loss (e.g., a time-lag constant) and hence relationships to combustion and fire behavior [*Deeming et al.*, 1977]. These diameter size classes have been shown to vary inversely with nutrient concentrations and improve calculations of loss or redistribution by fire [*Kauffman et al.*, 1993, 1994]. Sample plane lengths along the transects varied by wood diameter classes: 1 m for wood particles < 0.65 cm diameter; 2 m for wood debris 0.65 – 2.54 cm diameter; 5 m for wood debris 2.55 – 7.62 cm diameter; and 11 m for wood debris ≥ 7.63 cm diameter. For the pasture site, however, the sampling plane length for the wood debris diameter class ≥ 7.63 cm was 15 m. Biomass of the three wood debris diameter classes < 7.63 cm, was calculated using the quadratic mean diameters of each size class [*Kauffman et al.*, 1995, 1998]. For each of these classes, we simply counted those that intersected the transects. However, we measured the diameter of all wood particles ≥ 7.63 cm intersecting each sample plane.

Biomass of attached foliage (i.e., leaves, flowers, and seeds that remained attached to the slashed woody debris) was determined through calculation of the ratio between its biomass and that of the 0 - 0.64 cm diameter wood particles. At each site, 50 random samples of the < 0.65 cm diameter fuels and their associated attached foliage were collected, oven dried, and their mass ratios determined.

Along each transect, biomass of litter, grass, rootmat, seedlings, and sprouts found in 25 x 25 cm microplots in the pasture and 33 x 33 cm microplots in the primary forest sites were sampled. A microplot was placed at the 2 m

mark of each transect (i.e., n = 32 plots per site). The components collected within each microplot were separated, oven dried, and weighed. Following the burn, another microplot was established 2 m away from the prefire microplot, to determine postfire mass of these components. Ash mass was determined using 16 - 50 x 50 cm microplots on the day following the fire. Ash was collected using a portable vacuum cleaner with a generator.

2.4. Nutrient Pools

Aboveground nutrient pools were partitioned into the same components as those of biomass. Five samples of each component, with each sample consisting of a composite of 10 - 20 random collections of materials, were collected just prior to site burning. Nutrient concentration of ash was determined from the same samples collected to determine mass.

Total C, N, and S were analyzed by the induction furnace method utilizing a Carlo-Erba NA Series 1500 CNS analyzer [*Nelson and Sommers*, 1982]. Prior to analysis, plant and ash samples were dried to constant weight at 60 - 80°C and ground to pass through a 60 mesh screen (0.5 mm) in a Udy mill. The mass of C, N, and S was calculated by multiplying each of the biomass components for each transect by its respective nutrient concentration.

3. Results

3.1. Fire Behavior and Fuel Conditions

All fires were ignited midday, the time with the highest temperatures (33 - 35°C) and lowest relative humidity (49 - 52%). The pasture fire was ignited on September 2, 1995, at 1517 hours. The temperature just prior to setting the fire was 35°C and the relative humidity was 49% (Table 1). Shortly following ignition, strong wind gusts of up to 40 km h^{-1} were created by a downdraft from a nearby thunderstorm. The high winds resulted in rapid rates of spread and high flame lengths. This head fire resulted in a mean flame length of 3 ± 0.4 m.

Prior to ignition, moisture content was 5% for dead grass, 142% for live grass, and 143% for dicot seedlings (Table 1). Pasture wood debris (> 7.6 cm diameter) moisture content was 8%.

The Balteke primary forest slash fire was ignited on September 4, at 1204 hours. The temperature just prior to lighting was 34°C with a relative humidity of 50% (Table 1). After approximately 20 min, the fire was burning around the perimeter. Fire had carried through the site after approximately 50 min. Mean flame length was 13 ± 3 m.

The Sergipe forest fire was ignited on September 6, 1995, at 1304 hours. The temperature was 33°C with a relative humidity of 52% (Table 1). Ten minutes following ignition, the site perimeter was burning. Mean flame length was 8.2 ± 1.0 m. Mean fuel moisture contents for primary forest litter ranged from 4 - 7%, foliage 6 - 8%, and for woody debris 5 - 21%.

2.2. Aboveground Biomass

After 12 years of land use, the pasture biomass was low relative to the primary forests (Table 2). TAGB for the cattle pasture site was 66 Mg ha^{-1} before fire and 46 Mg ha^{-1} after fire. The combustion factor, defined as the percent of the TAGB (or fuels) consumed by the fire, was 31%. Residual coarse wood debris from the forest that originally occupied the site comprised 81% of the prefire TAGB in the pasture. Coarse wood debris comprised 95% of the total TAGB after fire. The combustion factor for fine and coarse wood debris was 69% and 19%, respectively. Surface fuels (i.e., grass and dicot seedlings), having accumulated since the last fire in the pasture, comprised 15% of prefire TAGB and had a combustion factor of 93%. High combustion factors for surface fuels and fine wood debris are important, since these are the fuels primarily consumed during the flaming phase of combustion. Also, these components are substantially higher in N and S than are coarse wood debris (Table 3). The quantity of ash was approximately 3 Mg ha^{-1}, or 5 % of postfire TAGB.

Biomass of the primary forest sites were about sixfold greater than that of the pasture (Table 2). The TAGB of the Balteke primary forest slash site was 355 Mg ha^{-1} prefire and 188 Mg ha^{-1} postfire (i.e., a 47% combustion factor). Wood debris at this site comprised 93% of the prefire TAGB and 98% for postfire TAGB with a combustion factor of 44%. Of the prefire TAGB, the coarse and fine wood debris composed 73% and 20% and following fire 90% and 8% of TAGB, respectively. Similar to the pasture site, the primary forest sites had high combustion factors for surface fuels. In the Balteke site, the combustion factor for surface fuels (i.e., litter, rootmat, and dicot seedlings) was 100%. Ash mass was 8 Mg ha^{-1}, or 4 % of postfire TAGB.

The TAGB of the Sergipe primary forest slash site was 399 Mg ha^{-1} prefire and 185 Mg ha^{-1} postfire (i.e., a 54% combustion factor; Table 2). Wood debris comprised 94% of the TAGB before fire and 99% following fire with a combustion factor of 51%. Coarse and fine wood debris comprised 74% and 20%, respectively, of the prefire TAGB. The combustion factor for coarse wood debris, fine wood debris, and surface fuels was 42%, 83%, and 96%, respectively. Ash comprised 10 Mg ha^{-1}, or 5% of postfire TAGB.

In terms of total site biomass comparisons, the Sergipe primary forest slash site (3.4 ha) was approximately half the size of the pasture site (6.9 ha) but had about 3 times the biomass. Similarly, the Balteke primary forest site (1.5 ha) was only ≈20% of the size of the pasture site but contained 16% more TAGB.

Twelve years following the initial forest slash burn, TAGB of the pasture site was ≈19% that of the forest study sites. Woody debris in the sampled pasture was equivalent to ≈16% of the woody biomass in the forest sites of this study (Table 2). Assuming the forest and pasture sites are typical in terms of biomass and consumption, then ≈81% of the original forest biomass and ≈84% of the coarse wood debris biomass at the pasture site had disappeared through combustion losses during the three previous fires and through decomposition. This is reasonable since fire consumed about half of the TAGB of slashed primary forest (Table 2) [*Kauffman et al.,* 1995].

3.3. Aboveground Nutrient Pools

Nutrient concentration of N in surface fuels (i.e., litter, grass, dicot seedlings, and rootmat) was higher in the forest sites than in the pasture site (Table 3). C and S concentrations were similar between the pasture and forest sites. As would be expected, N and S concentrations of surface fuels for all sites were higher than woody debris. Surface fuels are typically completely consumed by fire (Table 3), underscoring their importance as a source of N and S emissions. Concentrations of N and S in woody debris components at all sites were inversely related to stem diameter.

Concentrations of C for nonwood fuels ranged from 43 to 48% in the pasture site, and from 31 to 51% for the primary forest sites (Table 3). For the woody components, C ranged from 48 to 52% for all sites. Mean attached foliage C concentration was 51% for the primary forest sites. Because of the high quantity of C lost during combustion, C concentration in ash was about half (18 – 25%) the concentrations of the uncombusted biomass.

In the primary forest slash, concentrations of N for surface fuels were about twice that of the pasture (Table 3). N concentrations of the nonwood fuels in the forests were about twofold greater than that of the wood debris. The mean N concentration of ash was low; similar to that of coarse wood debris. This is likely related to the low temperature of volatilization of N, resulting in most being lost via combustion processes [*Kauffman et al.*, 1993].

Mean S concentrations for the non-woody components ranged from approximately 1 to 3 mg g^{-1} for primary forest and pasture sites (Table 3). Mean S concentrations of the woody component were lower (≈1 mg g^{-1}). In contrast to N and C, the S concentration in ash typically exceeded concentrations in the uncombusted fuels.

The aboveground C pool of the pasture site was about 19% that of the primary forest sites (i.e., 34 Mg C ha^{-1} versus 173 and 195 Mg C ha^{-1}; Table 4). In the pasture, the prefire C mass of residual coarse wood debris was 28 Mg C ha^{-1} or 84% of the total prefire C pool. The pasture fire resulted in a C loss of ≈ 9 Mg C ha^{-1}. Ash comprised a minor proportion of the postfire C pool (≈ 4%).

C mass of coarse wood in the primary forests was 127 and 144 Mg C ha^{-1}, representing 74% of the prefire aboveground C pool. C loss associated with biomass burning in the primary forests was 79 and 102 Mg C ha^{-1}. Given the greater biomass as well as the higher combustion factor, C losses by fire were over 8 times greater than that from the pasture. In the forest slash sites, the C pool of ash was approximately 2 Mg ha^{-1}, or 2% of the postfire C pool.

In the pasture, the prefire aboveground N pool was ≈16% that of the primary forest slash sites (Table 5). At all sites, the largest proportion of the N pool was found in the wood debris components (i.e., 73% in the pasture and ≈51% in the forest slash).

Nonwood debris comprised 15% of the pasture TAGB and ≈6% of the forest TAGB. However, this component comprised 21% of the pasture N pool and ≈15% of the forest N pool. Fire resulted in a considerable loss of N from the primary forest sites (i.e., 1019 and 1196 kg N ha^{-1} or 56% of the prefire pool). The proportion of N lost from the forests slash sites exceeded the proportion of biomass consumed by fire. Both the proportion and mass of site losses in the pasture were lower (≈12% of the prefire pool). Ash comprised 9% of the postfire N pool in the pasture and 12% in the forest sites.

The total aboveground S pool prior to burning in the pasture was ≈22% that of the forest sites (Table 6). In all sites, most of the S pool (54 - 72%) was sequestered in the coarse wood debris (≥ 7.63 cm diameter). Nonwoody debris comprised 13 to 23% of the S pool, although only represented 6 to 15% of TAGB. In the forest sites, attached foliage only comprised 2 - 3% of the TAGB; however, it comprised 11 – 13% of the S pool. Forest S losses were 87 kg S ha^{-1} and 96 kg S ha^{-1}, respectively, or about 49% of the total prefire S pool. Losses in the pasture were much lower, 4.6 kg S ha^{-1} or 12% of the total prefire pool was lost during the fire. The proportion of S lost was lower than that for C and N and especially lower in the pasture site. The S in ash comprised 14 – 27% of the postfire pool for all sites; a higher proportion to the postfire S pool than both C and N pools.

4. Discussion

It is well known that the global biogeochemical consequences of large-scale deforestation and land conversion in the Amazon are considerable. Losses of biomass and nutrients as a result of these anthropogenic processes arise from aerosol transport, trace gas losses, erosion, and leaching following fire. Our results indicate a greater quantity of emissions arise from the burning of primary forest than from pasture burning in Amazonia. Even though emissions are low in pasture fires, they are burned quite frequently (every 2 – 3 years). Therefore the cumulative emissions over the useful life of a pasture could rival those arising from primary forest slash burning.

We assumed that any portion of the prefire nutrient pool that did not remain in either the residual unburned biomass or ash was an atmospheric emission. Total C inputs into the atmosphere ranged from 9 Mg ha^{-1} (pasture site) to 102 Mg ha^{-1} (Sergipe forest site, Table 4). Compared to data presented by *Kauffman et al.* [1995], the Sergipe forest site had the highest C loss from a burn yet measured in Rondônia (Table 7). This is due to the relatively high biomass for this site coupled with a relatively high combustion factor (54%). Similarly, a high N loss of 1196 kg ha^{-1} was measured at the Sergipe primary forest site.

The biomass, elemental losses, and combustion factors of the sites sampled during the 1995 SCAR-B experiment were similar to other biomass burns in Rondônia and Pará (Table 7)[*Kauffman et al.*, 1995, 1998]. Based on this review, we have found that TAGB of pastures ranged from 53 to 119 Mg ha^{-1} and combustion factors range from 21 to 83% (Table 7). C emissions arising from pasture biomass burning range from 9 to 21 Mg ha^{-1}. Pasture fires contribute to ranges of nutrient losses of 88 - 261 kg N ha^{-1} and 5 - 25 kg S ha^{-1}. C, N, and S losses from the pasture burning in this study were the lowest measured for Rondônia and Pará.

In the studies of primary slashed forests, TAGB ranged from 290 to 435 Mg ha^{-1}. This was similar for the biomass of intact tropical forests of northern Rondônia measured by Cummings [1997]. In a review of primary forest slash fires in Rondônia and Pará, the mean combustion factor ranged from 38 to 57 % (Table 7). C emissions ranged from 58 to 112 Mg ha^{-1}. If these sites are representative of all sites of deforestation, we estimate that a deforestation rate of 11,000 – 19,000 km^2 yr^{-1} [*Fearnside*, 1992] would yield a range of C emissions of 64 – 213 Tg yr^{-1}.

In the Amazon, N losses from biomass burning in slashed primary forest ranged from 817 - 1605 kg ha^{-1}, globally among the highest losses ever measured from biomass burning of wildland fuels [Kauffman et al., 1995]. Losses of S as emissions from primary forest burning range from 87 to 137 kg ha^{-1}.

Pasture maintenance and forest clearing are the two land use scenarios in which biomass burning is commonly utilized (Figure 1 and Table 7). Both the quantity of biomass consumed and the chemical composition of the fuels will vary by land use and years since deforestation or land use change [*Kauffman et al.*, 1998]. In a region where deforestation is a widespread phenomenon, we would expect that the chemical composition of emissions would change as the source of emissions shift from predominantly primary forest to pasture fires. Because pastures are typically burned every 2 - 3 years for maintenance in the first 10 years following establishment, the areal extent of this type of biomass burning must far exceed that of forests in heavily deforested regions of the Amazon. *Kauffman et al.* [1998] suggested that if 15,000 – 19,000 km^2 of forest are burned each year (as reported by *Fearnside* [1992] and *Skole and Tucker* [1993]) and if these forests were converted to pasture, pasture fires might be burning at a rate of 45,000 to 95,000 km^2 yr^{-1}. In other words, burning occurs on as much as 11 to 24 % of the ≈400,000 km^2 of the Amazon that has been deforested to date. If true, then the contribution of emissions arising from pasture fires could rival that of slash fires. Using the C emissions range of 9 – 21 Mg ha^{-1} from pasture burning and 58 – 112 Mg ha^{-1} from primary forest slash fires in Rondônia and Pará, we predict C losses of 41 - 200 Tg yr^{-1} from pastures and 87 – 213 Tg yr^{-1} from primary forest slash fires. If our numbers are reasonably accurate, then pasture fires are clearly an important global emission source. Improved estimates of deforestation and land use by remote sensing and long-term ground studies of biomass and nutrient dynamics of regions undergoing deforestation, cultivation, and cattle ranching are needed to decrease the uncertainties in estimates of the quantity of emissions from biomass burning in the Amazon.

The magnitude of elemental losses from biomass burning is not only important from an atmospheric/biogeochemical perspective. Losses of this magnitude likely decrease ecosystem productivity, including the capacity for these systems to function as carbon sinks or provide sustainable resources in the future. With such rapid ecosystem nutrient losses coupled with the remarkable loss of species diversity, the recovery of the integrity and productivity of the original forest is not likely to be regained following abandonment. This underscores the need to develop sustainable land use systems in the Amazon.

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LIST OF CAPTIONS

Figure 1. A generalized pattern of land use in the Brazilian Amazon. The process begins with primary or intact forest being selectively logged or converted to pasture or shifting cultivation. Typically, shifting cultivation cycles consist of 2 – 3 years of active use followed by a 4-year fallow period. Pastures can be productive for > 20 years. Fire is typically used for maintenance of pastures and each time slashed primary or secondary forests are converted to shifting cultivation or pasture.

TABLE 1. Weather conditions at the time of burning, fuel moisture (% dry wt. basis), and flame length (m) of flame front during a pasture fire and two primary forest slash fires in Rondônia, Brazil during the SCAR-B Mission.

TABLE 2. Aboveground biomass (Mg ha^{-1}) before and after fire during the SCAR-B mission for a pasture and primary forests near Jamarí, Rondônia, Brazil. Numbers are means ± standard errors.

TABLE 3. Nutrient concentration of aboveground biomass and ash of a livestock pasture and two slashed primary forests during the SCAR-B Mission in Rondônia, Brazil, 1995. Numbers are means ± standard errors.

TABLE 4. Aboveground carbon (Mg ha^{-1}) before and after fire, and site loss (Mg ha^{-1}) during the SCAR-B mission for a pasture and primary forests near Jamarí, Rondônia, Brazil. Numbers are means ± standard errors.

TABLE 5. Aboveground nitrogen (kg ha^{-1}) before and after fire, and site loss (kg ha^{-1}) during the SCAR-B mission for a pasture and primary forests near Jamarí, Rondônia, Brazil. Numbers are means ± standard errors.

TABLE 6. Aboveground sulfur (kg ha^{-1}) before and after fire, and site loss (kg ha^{-1}) during the SCAR-B mission for a pasture and primary forests near Jamarí, Rondônia, Brazil. Numbers are means ± standard errors.

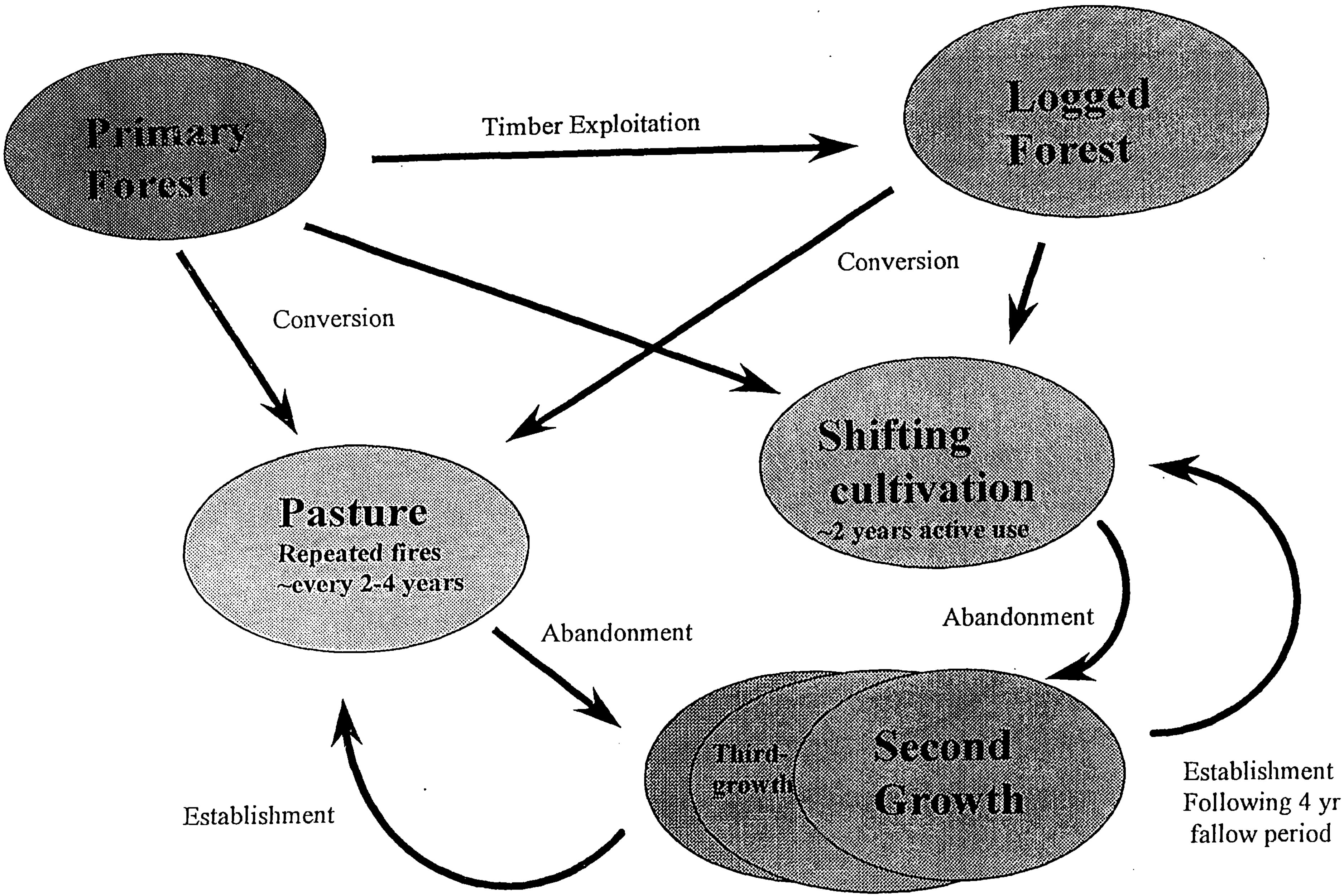
Primary Forest
Timber Exploitation
Logged Forest
Conversion
Conversion
Shifting cultivation
~2 years active use
Pasture
Repeated fires
~every 2-4 years
Abandonment
Abandonment
Third-growth
Second Growth
Establishment
Establishment
Following 4 yr
fallow period

TABLE 7. Range of and mean total aboveground biomass (Mg ha^{-1}), combustion factors (%), and nutrient losses for selected land cover types in Pará and Rondônia (1990 - 1995).

TABLE 1. Weather conditions at the time of burning, fuel moisture (% dry wt. basis), and flame length (m) of flame front during a pasture fire and two primary forest slash fires in Rondônia, Brazil during the SCAR-B Mission.

	Pasture	Primary Forest Slash - Balteke	Primary Forest Slash - Sergipe
Date of burn	2 September 1995	4 September 1995	6 September 1995
Temperature (°C)	35	35	33
Relative humidity (%)	49	50	52
Moisture content (%)			
Soil surface	16.9±3.0	24.5±2.8	28.8±2.1
Litter	n/a	3.5±0.7	6.8±0.7
Residual Grass	4.7±1.1	n/a	n/a
Grass	142.0±26.1	n/a	n/a
Dicot Seedlings	143.3±7.9	n/a	197.2±30.6
Attached foliage	n/a	5.6±0.7	7.7±0.5
Wood debris (cm diam)			
0.0-0.64	n/a	4.5±0.7	n/a
0.65-2.54	n/a	8.4±0.4	12.3±0.4
2.55-7.62	n/a	6.5±0.4	n/a
> 7.63 cm diam.	7.8±1.1	20.0±9.5	21.1±6.8
Flame length (m)	3.0±0.4	12.8±3.1	8.2±1.0

*n/a: Not present or not measured.

TABLE 2. Aboveground biomass (Mg ha^{-1}) before and after fire during the SCAR-B mission for a pasture and primary forests near Jamarí, Rondônia, Brazil. Numbers are means ± standard errors.

Component	Pasture		Primary Forest Slash - Balteke		Primary Forest Slash - Sergipe	
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter	n/a*	n/a	7.3±0.9	0.0±0.0	12.4±1.1	0.5±0.3
Residual Grass	9.3±0.8	0.6±0.2	n/a	n/a	n/a	n/a
Grass	0.2±<0.1	0.0±0.0	n/a	n/a	n/a	n/a
Dicot Seedlings	0.4±0.1	<0.1±<0.1	0.2±0.1	0.0±0.0	0.5±0.3	0.1±0.0
Rootmat	n/a	n/a	6.9±1.5	0.0±0.0	3.2±0.8	0.0±0.0
Attached Foliage	n/a	n/a	8.9±1.3	1.0±0.6	7.9±1.0	0.4±0.2
Wood Debris (cm diam)						
0 - 0.64	0.1±<0.1	<0.1±<0.1	4.6±0.7	0.5±0.3	4.7±0.6	0.2±0.1
0.65-2.54	0.5±0.2	0.1±<0.1	17.9±2.0	2.2±0.7	15.6±1.6	1.5±0.5
2.55-7.62	1.0±0.4	0.3±.2	46.9±5.4	12.0±2.2	59.8±7.9	12.0±2.1
7.63-20.5 Sound	7.8±2.3	5.5±1.6	73.5±8.3	61.3±7.2	83.7±9.6	52.6±6.3
7.63-20.5 Rotten	0.3±0.2	0.0±0.0	2.1±0.9	0.0±0.0	3.0±1.3	0.1±0.0
>20.5 Sound	45.5±12.3	37.9±10.3	164.8±41.2	104.8±32.7	206.1±39.5	117.2±30.0
>20.5 Rotten	0.0±0.0	0.0±0.0	19.1±8.0	3.2±2.4	0.7±0.0	0.0±0.0
Palm	1.2±0.0	1.2±0.0	2.5±1.8	2.5±1.7	1.1±0.0	0.6±0.0
Total Biomass	66.3 ± 13.3	45.6 ± 11.0	354.8 ± 47.8	187.5 ± 35.8	398.8 ± 44.7	185.2 ± 30.0
Ash		2.5 ± 0.2		8.1 ± 1.4		9.6 ± 0.9
Combustion Factor (%)		31		47		54

*n/a: Not present in transects.

TABLE 3. Nutrient concentration of aboveground biomass and ash of a livestock pasture and two slashed primary forests during the SCAR-B Mission in Rondônia, Brazil, 1995. Numbers are sample averages from sites. Numbers are means ± standard errors.

Component	Pasture - João			Primary Forest Slash - Balteke			Primary Forest Slash - Sergipe		
	Carbon (%)	Nitrogen ($mg\ g^{-1}$)	Sulfur ($mg\ g^{-1}$)	Carbon (%)	Nitrogen ($mg\ g^{-1}$)	Sufhur ($mg\ g^{-1}$)	Carbon (%)	Nitrogen ($mg\ g^{-1}$)	Sulfur ($mg\ g^{-1}$)
Ash	22.2±1.7	7.4±0.4	2.0±0.2	25.4±2.2	11.7±0.9	2.2±0.3	18.4±1.1	9.8±1.1	2.8±0.4
Litter	n/a*	n/a	n/a	47.8±0.8	21.8±0.9	1.5±0.1	46.7±0.4	19.8±0.6	1.5±0.1
Dicot Seedlings	47.7±0.3	10.7±0.4	1.1±0.2	46.9±0.4	19.0±2.1	1.3±0.2	46.9±0.4	19.0±2.1	1.3±0.2
Rootmat	n/a	n/a	n/a	32.6±1.1	17.6±0.9	1.6±0.1	30.6±2.3	16.0±1.0	1.4±0.1
Dead Grass	43.0±0.9	6.3±0.9	0.9±0.1	n/a	n/a	n/a	n/a	n/a	n/a
Grass	45.7±0.8	5.6±0.4	1.1±0.1	n/a	n/a	n/a	n/a	n/a	n/a
Attached Foliage	n/a	n/a	n/a	51.1±0.3	23.3±1.9	2.6±0.2	51.1±0.3	23.3±1.9	2.6±0.2
Wood Debris	(cm diam)								
0-0.64	49.2±0.3	7.7±0.2	0.8±0.2	48.2±0.2	11.7±0.1	1.2±0.1	48.2±0.2	11.7±0.1	1.2±0.1
0.65-2.54	49.7±0.2	5.3±0.7	0.5±<0.1	48.7±0.2	7.5±0.4	0.5±<0.1	48.7±0.2	7.5±0.4	0.5±<0.1
2.55-7.62	50.0±0.2	3.9±1.0	0.4±0.2	49.2±0.1	4.6±0.3	0.5±<0.1	49.2±0.1	4.6±0.3	0.5±<0.1
>7.63	52.0±0.3	4.0±0.4	0.5±0.3	49.1±0.1	3.5±0.3	0.4±<0.1	49.1±0.1	3.5±0.3	0.4±<0.1
Palm	48.0±<0.1	6.9±0.9	1.0±0.1	n/a	n/a	n/a	n/a	n/a	n/a

*n/a: Not present in transects or not measured.

TABLE 4. Aboveground carbon (Mg ha^{-1}) before and after fire and site loss (Mg ha^{-1}) during the SCAR-B mission for a pasture and primary forests near Jamarí, Rondônia, Brazil. Numbers are means ± standard errors.

Component	Pasture		Primary Forest Slash - Balteke		Primary Forest Slash - Sergipe	
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter	n/a*	n/a	3.5±0.4	0.0±0.0	5.8±0.5	0.2±0.1
Residual Grass	4.0±0.3	0.3±0.1	n/a	n/a	n/a	n/a
Grass	0.1±<0.1	0.0±0.0	n/a	n/a	n/a	n/a
Dicot Seedlings	0.2±<0.1	<0.1±<0.1	0.1±<0.1	0.0±0.0	0.2±0.1	0.1±0.0
Rootmat	n/a	n/a	2.3±0.5	0.0±0.0	1.0±0.3	0.0±0.0
Attached Foliage	n/a	n/a	4.5±0.6	0.5±0.3	4.1±0.5	0.2±0.1
Wood Debris (cm diam)						
0 - 0.64	<0.1±<0.1	<0.1±<0.1	2.2±0.3	0.3±0.2	2.3±0.3	0.1±<0.1
0.65-2.54	0.2±0.1	0.1±<0.1	8.7±1.0	1.1±0.3	7.6±0.8	0.7±0.2
2.55-7.62	0.5±0.2	0.1±0.1	23.1±2.6	5.9±1.1	29.4±3.8	5.9±1.0
7.63-20.5 Sound	4.1±1.2	2.9±0.8	36.1±4.0	30.1±3.5	41.1±4.6	25.8±3.0
7.63-20.5 Rotten	0.2±0.1	0.0±0.0	1.0±0.4	0.0±0.0	1.5±0.6	0.1±0.0
>20.5 Sound	23.7±6.3	19.7±5.3	80.9±19.9	51.4±15.8	101.2±19.1	57.5±14.5
>20.5 Rotten	n/a	n/a	9.4±3.8	1.6±1.1	0.3±0.0	0.0±0.0
Palm	0.6±0.0	0.6±0.0	1.3±0.9	1.2±0.8	0.5±0.0	0.3±0.0
Ash		0.5±<0.1		2.1±0.2		1.8±0.1
Total Aboveground C	33.5±6.8	24.1±5.6	173.1±23.1	94.1±17.4	195.0±21.6	92.7±14.5
Site Loss		9.4±2.0		78.9±12.2		102.3±15.3

* n/a: Not present in transects.

TABLE 5. Aboveground nitrogen (kg ha^{-1}) before and after fire and site loss (kg ha^{-1}) during the SCAR-B mission for a pasture and primary forests near Jamari, Rondônia, Brazil. Numbers are means ± standard errors.

Component	Pasture		Primary Forest Slash - Balteke		Primary Forest Slash - Sergipe	
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter	n/a*	n/a	158.5±18.8	0.0±0.0	246.5±20.8	10.0±6.4
Residual Grass	58.6±5.2	3.8±1.0	n/a	n/a	n/a	n/a
Grass	1.1±0.2	0.0±0.0	n/a	n/a	n/a	n/a
Dicot Seedlings	4.66±1.0	0.1±<0.1	3.6±1.3	0.0±0.0	9.8±4.9	2.5±0.0
Rootmat	n/a	n/a	121.8±25.6	0.0±0.0	50.6±13.6	0.0±0.0
Attached Foliage	n/a	n/a	207.2±28.9	23.9±14.4	184.8±23.8	8.5±4.1
Wood Debris (cm diam)						
0 - 0.64	0.4±0.1	0.3±0.2	54.4±7.6	6.3±3.8	55.7±7.1	2.6±1.2
0.65-2.54	2.4±0.1	0.5±0.2	134.4±15.1	16.4±4.9	117.1±11.9	11.0±3.7
2.55-7.62	3.9±0.2	1.1±0.6	214.9±24.5	55.1±10.1	273.8±36.2	55.1±9.5
7.63-20.5 Sound	31.6±9.2	22.2±6.5	260.7±28.9	217.5±25.2	297.1±34.1	186.8±22.3
7.63-20.5 Rotten	1.2±0.7	0.0±0.0	7.6±3.1	0.0±0.0	10.7±4.7	0.4±0.0
>20.5 Sound	183.6±49.6	153.0±41.7	584.9±143.7	371.9±114.2	731.6±140.1	415.8±1.6.6
>20.5 Rotten	n/a	n/a	67.7±27.8	11.4±8.2	2.4±0.0	0.0±0.0
Palm	8.0±0.0	8.0±0.0	9.0±6.3	8.7±6.1	3.8±0.0	2.1±0.0
Ash		18.1±1.2		94.5±11.0		93.5±6.1
Total Aboveground N	295.4±54.1	207.0±44.8	1824.7±188.0	805.7±143.4	1983.9±173.7	788.2±107.1
Site Loss		88.4±16.2		1019.0±118.4		1195.6±140.5

*n/a: Not present in transects.

TABLE 6. Aboveground sulfur (kg ha^{-1}) before and after fire and site loss (kg ha^{-1}) during the SCAR-B mission for a pasture and primary forests near Jamarí, Rondônia, Brazil. Numbers are means ± standard errors.

Component	Pasture		Primary Forest Slash - Balteke		Primary Forest Slash - Sergipe	
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter	n/a*	n/a	11.2±1.3	0.0±0.0	19.3±1.6	0.8±0.5
Residual Grass	8.3±0.7	5.4±1.4	n/a	n/a	n/a	n/a
Grass	0.2±<0.1	0.0±0.0	n/a	n/a	n/a	n/a
Dicot Seedlings	0.5±0.1	<0.1±<0.1	0.3±0.1	0.0±0.0	0.7±0.3	0.2±0.0
Rootmat	n/a	n/a	11.3±2.4	0.0±0.0	4.5±1.2	0.0±0.0
Attached Foliage	n/a	n/a	23.2±3.2	2.7±1.6	20.7±2.7	1.0±0.5
Wood Debris (cm diam)						
0 - 0.64	<0.1±<0.1	<0.1±<0.1	5.5±0.8	0.6±0.4	5.6±0.7	0.3±0.1
0.65-2.54	0.2±0.1	0.1±<0.1	8.2±0.9	1.0±0.3	7.1±0.7	0.7±0.2
2.55-7.62	0.4±0.2	0.1±0.1	21.3±2.4	5.5±1.0	27.1±3.6	5.5±0.9
7.63-20.5 Sound	4.1±1.2	2.8±0.8	27.1±3.0	22.6±2.6	30.9±3.5	19.4±2.3
7.63-20.5 Rotten	0.2±0.1	0.0±0.0	0.8±0.3	0.0±0.0	1.1±0.5	<0.1±0.0
>20.5 Sound	23.5±6.3	19.6±5.3	60.8±14.9	38.7±11.9	76.1±14.6	43.2±11.1
>20.5 Rotten	n/a	n/a	7.0±2.9	1.2±0.9	0.3±0.0	0.0±0.0
Palm	1.2±0.0	1.2±0.0	0.9±0.6	0.9±6.3	0.4±0.0	0.2±0.0
Ash		4.8±0.3		17.4±2.0		26.6±1.7
Total Aboveground S	38.6±6.9	34.0±6.1	177.5±19.1	90.6±15.2	193.7±17.8	97.8±11.1
Site Loss		4.6±2.6		87.0±12.1		95.9±14.2

*n/a: Not present in transects.

TABLE 7. Range of and mean total aboveground biomass (TAGB) ($Mg\ ha^{-1}$), combustion factors (%), and nutrient losses for selected land cover types in Pará and Rondônia (1990 - 1995).

Component	TAGB ($Mg\ ha^{-1}$)	Combustion Factor (%)	C ($Mg\ ha^{-1}$)	N ($kg\ ha^{-1}$)	S ($kg\ ha^{-1}$)	Cite
Primary Forest Slash						
Pará (n=2)	292, 435	52	76, 112	817, 1387	109, 137	Kauffman et al. 1995
Rondônia (n=5)	290 - 399	38-57	58-102	1019-1605	87-122	Kauffman et al. 1995, Kauffman et al. unpublished, Guild et al. this paper
Mean (n=7)	349 ± 21	48 ± 2	88 ± 8	1181 ± 115	107 ± 8	
Livestock Pasture						
Pará (n=1)	53	83	21	261	25	Kauffman et al. In press.
Rondônia (n=4)	60 - 119	21-47	9-16	88-240	5-19	Kauffman et al. In press, Kauffman et al. unpublished, Guild et al. this paper
Mean (n=5)	74 ± 12	46 ± 10	14 ± 3	199 ± 39	16 ± 4	

TABLE_8. Aboveground Biomass (Mg/site) Before and After Fire During the SCAR-B Mission for Sampled Pasture and Primary Forests near Jamari, Rondônia, Brazil.

	Pasture (6.9 ha)		Primary Forest Slash - 1 (1.5 ha)		Primary Forest Slash - 2 (3.4 ha)	
Burn Date	2 September 1995		4 September 1995		6 September 1995	
Component	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Surface Fuels	68.6 ± 6.2	4.2 ± 1.1	21.4 ± 2.5	0.0	54.4 ± 4.6	2.1 ± 1.5
Fine Wood Debris	10.4 ± 3.1	2.9 ± 1.1	116.6 ± 10.4	23.5 ± 4.4	297.4 ± 30.2	47.5 ± 8.9
Coarse Wood Debris	377.2 ± 91.1	306.7 ± 75.5	389.9 ± 68.8	255.6 ± 50.8	994.7 ± 140.7	575.6 ± 100.5
Total Biomass	**456.2 ± 91.5**	**313.7 ± 75.6**	**527.9 ± 71.1**	**279.1 ± 53.2**	**1346.5 ± 150.8**	**625.3 ± 101.3**
Ash		16.9 ± 1.6		12.1 ± 2.0		32.2 ± 3.0

Total aboveground biomass, elemental pools, and combustion factors of fires sampled during the SCAR-B Experiment

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Abstract

In association with ground and airborne emissions measurements made by INPE, USFS, and USP scientists, we sampled the total aboveground biomass (TAGB) and pools of N, C, and S prior to burning and following fire in two slashed primary forests and one cattle pasture in Rondônia Brazil. From these data, we project the total quantity of elements lost to the atmosphere during biomass burning. TAGB of the slashed primary forests before fire was 399 and 355 Mg ha^{-1}. Following fire, 185 and 188 Mg ha^{-1} of wood debris remained (i.e., a combustion factor of 54 and 48%, respectively). Prefire biomass of the cattle pasture was 66 Mg ha^{-1} and the biomass combustion factor was 31%. Total elemental inputs to the atmosphere (or site losses) arising from the primary forest slash fires was 80-103 Mg C ha^{-1}, 1064-1368 kg N ha^{-1}; and 86-112 kg S ha $^{-1}$. The cattle pasture losses were substantially lower than that of the primary forest burns: 9.7 Mg C ha^{-1}; 93 kg N ha^{-1}; and 4.0 kg S ha^{-1}. However, given that pastures are frequently burned as often as every two years, their cumulative inputs to the atmosphere are likely significant sources of emissions in the Amazon. The biomass, elemental losses and combustion factors of the sites sampled during the 1995 SCAR-B experiment were similar to results from other biomass burns in Rondônia and Para. For all studies combined, we have found that TAGB of primary slashed forests range from 290-435 Mg ha^{-1}. Combustion factors of fires at these sites range from 38-57%. For pastures, TAGB ranges from 59-119 Mg ha^{-1} and combustion factors range from 31-81%. This pasture represents the low end of emissions for all sites measured. Carbon emissions arising from biomass burning ranged from 58-112 Mg ha^{-1} in slashed primary forests and from 10-21 Mg ha^{-1} in cattle pastures. Nitrogen losses from biomass burning in slashed primary forest range from 817-1605 kg ha^{-1}; globally among the highest losses ever measured from biomass burning. The magnitude of these losses are of importance not only from an atmospheric/biogeochemical stand point, but indicate the need to develop sustainable land use systems in the Amazon. Losses of this magnitude likely decrease ecosystem productivity including the capacity for these systems to function as C sinks or provide sustainable resources in the future.

Introduction

In September 1995, we sampled the total aboveground biomass (TAGB), elemental pools and the subsequent losses and redistribution associated with biomass burning of two slashed primary forests and one cattle pasture. All methods of biomass and nutrient analysis are similar to that of Kauffman et al. (1995). The sampled sites were areas that had been slashed prior to our arrival by landowners of small subsistence farms (sitios) in Rondônia. To minimize the scientific interference, all decisions of when to burn and the methods of burning were left to the land owners. With the land owner's permission, we sampled the sites prior to, and immediately following burning. All of the areas were legally burned. The burns were conducted on the 2, 4, and 6 September 1995, respectively. The specific locations of the site (from a Global Positioning System) are: Primary forest-1: 9° 11' 48.6"S, 63° 07' 22"W; Primary forest-2: 9° 11' 49.0" S, 63° 07' 22"W; and the cattle pasture: 9° 10' 42.6"S, 63° 10' 3"W. In addition to our ground-based studies of biomass and elemental dynamics, airborne and ground-based emissions for these sites were also measured (see studies by Babbitt et al.).

Results and Discussion

Biomass of the slashed primary forests were 355 and 399 Mg ha^{-1}. Coarse wood debris composed the majority (74%) of this biomass. In contrast, biomass of the cattle pasture was <19% that of the primary forests (66 Mg ha^{-1}). In the cattle pasture, grasses and other fine surface fuels only comprised 15% of the TAGB. Residual wood resistant to decomposition originating from the primary forest that formerly occupied this site accounted for 83 % of the TAGB present in the pasture at the time of burning (Table 1). Virtually all of the fine surface fuels at all sites were consumed by fire. In addition, the combustion factor of the fine wood debris in the primary forest exceeded 80%. This is important because these are the majority of the fuel components that are consumed during the process of flaming combustion. They are also significantly higher in concentration of N, S, P and other cations than coarse wood debris. The majority of the biomass consumed was coarse wood debris. This component is likely consumed predominantly by smoldering combustion long after the passage of the flame front. Smoldering combustion of these sites occurred for 2-3 days following the day of the burn. Combustion factors for the primary forests were 48 and 54%. The combustion factor of the pasture burn was 31%.

Subsistence landowners tend to work relatively small plots. The small plots sampled in this study are representative of much of the land use in Rondônia. The pasture was ≈7 ha while the primary forest were 1.5 and 3.4 ha. Total biomass consumed during the three fires was 142 Mg ha^{-1} in the pasture and 248 and 721 Mg ha^{-1} in the two primary forests (Table 2).

We assume that any portion of the prefire nutrient pool that does not remain in either the residual unburned biomass or ash component was an atmospheric emission. C inputs into the atmosphere ranged from 9.6 Mg ha^{-1} during the pasture fire to 103 Mg ha^{-1} in primary forest-2. The latter is the highest C loss from a burn yet measured in Rondônia. This is related to the relatively high biomass for this site coupled with burning during an exceptionally dry period for Rondônia. Similarly high rates of N loss (1368 kg ha^{-1}) were encountered in this primary forest (Figure 1). In the Amazon, this level of N loss was only exceeded in a Para primary forest slash fire during an exceptionally dry year (Kauffman et al. 1995). Cumulatively, the losses of N on this site was 4620 kg ha^{-1} (Figure 2). Cumulative losses of S at this primary forest were 379 kg ha^{-1} and C losses were 347 Mg ha^{-1}. Cumulative losses in the pasture were 67 Mg C ha^{-1}, 4620 kg N ha^{-1} and 1583 kg S ha^{-1}. Because of the frequency in which cattle pastures are burned it is likely that more area of Rondônia is burned as cattle pasture than forest slash.

There are a variety of land uses in Rondônia in which biomass burning is a dominant activity. We sampled but two activities (pasture maintenance and forest clearing) in which biomass burning is utilized. Biomass burning is also commonly used in the reclearing of second and third growth forests for cultivation or pasture conversion (Table 3). Nutrient dynamics associated with biomass burning both in terms of mass loss and chemical composition will vary by each land use. Therefore, it is important to understand the land uses associated with source of the emissions. Through time we would expect the chemical composition of emissions to change as the source of emissions change from predominantly primary forest to pasture and second growth forests.

Literature Cited

Kauffman, J. B., D. L. Cummings, D. E. Ward and R. Babbitt. 1996. Fires in the Brazilian Amazon: Biomass, nutrient pools, and losses in slashed primary forests. Oecologia 104:394-408.

Fig. 1. The loss of biomass, total C, N and S as a result of biomass burning in a cattle pasture and two slashed primary forests during the SCAR-B Experiment near Jamari, Rondônia Brazil. Biomass and C is in Mg ha^{-1}, N is expressed as kg/10 ha^{-1}, and S is expressed in kg ha^{-1}.

Fig. 2. The cumulative loss of biomass, C, N and S based upon losses ha^{-1} and the size of the burned area for sampled sites near Jamari, Rondônia. The size of the areas can be found in Table 2. Biomass and C are expressed in Mg, N is expressed in kg/10 and S is expressed in kg.

III. Total aboveground biomass and structure of tropical forest delineated by projeto RADAMBRASIL in northern Rondonia, Brazil

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Total Aboveground Biomass and Structure of Tropical Forests Delineated by Projeto RADAMBRASIL in Northern Rondônia, Brazil.

Chapter 1

Introduction

The Brazilian Amazon contains the largest contiguous tropical forest in the world (World Resources, 1990) with a forested area estimated to have been 4 million km^2 prior to development for modern agriculture (Fearnside, 1993). Social, economic, and political pressures have contributed to the rapid loss of forest in the Amazon; deforestation rates averaged 15-22 x 10^5 ha y^{-1} from 1978 to 1988 (Skole et al, 1994; Fearnside, 1992a). As the forest disappeared farms, pastures, and cities spring up in the wake of its passing. The vast tracts of intact tropical forest that remain play an important part in global biogeochemical cycles (Schlesinger, 1991).

Global climate change has been a topic of scientific debate and concern (Detwiler and Hall, 1988, Dunnette and O'Brien, 1992, Houghton, 1995, and Schlesinger, 1991). Most scientists agree that there is a rise in the Earths' temperature due to increases in radiatively active gasses arising from human and natural activities. The dominant greenhouse gas is carbon dioxide (CO_2) which has steadily risen in the atmosphere during the last two centuries (Neftel et al., 1985, and Keeling, et al., 1989). The majority of the rise in the atmospheric CO_2 level is

due to emissions resulting from fossil fuel combustion related to industrialization, however, a significant portion (as much as 40%) is associated with deforestation and the resultant biomass burning (Crutzen and Andrea, 1990). There is general agreement among scientists that approximately one third of the atmospheric increase in CO_2 during the last century is the result of deforestation (Houghton and Skole, 1990). Prior to 1940, a majority of the CO_2 arising from deforestation came from temperate and boreal forests (Houghton, 1995). However, from 1940 to the present, deforestation in the tropics has become the dominant source (Houghton, 1995).

Based upon estimates of CO_2 inputs and current models of carbon mass balance, more carbon emissions occur than can be accounted for by accumulations in the atmosphere and oceans. Therefore, it is hypothesized that a carbon sink exists somewhere other than the atmosphere and oceans (SCEP, 1970; Bacastow and Keeling, 1973; Broecer et al., 1979; Keeling et al., 1989; Tans et al., 1990; Saninto et al., 1992). The theory of a "missing" carbon sink has inspired a profusion of research into its location. Research to accurately determine the dynamics of carbon cycling and carbon sinks in terrestrial ecosystems has led to numerous estimates of carbon flux for tropical ecosystems (Houghton, 1995; Hall and Uhlig, 1991; Fearnside, 1991,1997; Detwiler and Hall, 1988; Crutzen and Andrea, 1990; Dixon et al., 1994; Grace et al., 1995; Lugo and Brown, 1992). Tropical forests as carbon sinks may mitigate the rate of global climate change. Therefore, accurate determinations of carbon pools and flux in the tropical forests are essential for predictions of global climatic change.

There are many sources for discrepancies or errors in calculating carbon flux due to deforestation. Data are lacking on the: (1) area deforested; (2) biomass and C concentration per unit area; and (3) combustion factors and emissions factors from biomass burning. Accurate estimates of total biomass are important because small differences can have a multiplicative effect through each model used to determine carbon flux. There is a need for improvement in the dynamics and magnitude of all factors contributing to carbon flux calculations. This logically must begin with an improvement in our understanding of total aboveground biomass (TAGB) of tropical forests of the Amazon basin as well as scale models used in their estimation. Houghton (1991) identified several factors used in the models to estimate carbon flux that lead to uncertainties in the results derived from the models, including rates of deforestation, stocks of carbon per unit area, land use, and exchanges of biotic CO_2 not associated with deforestation. Determination of carbon stocks in deforested areas and losses of carbon associated with burning are ultimately dependent on accurate estimates of the biomass of primary forest.

This study quantified TAGB and forest structure of 20 forest inventory sites of Projeto RADAMBRASIL (Departamento National da Producão Mineral, Brasil, (DNPM) 1978). The specific objectives of this thesis are: (1) to determine the TAGB and structure of 20 intact primary forest sites (chapter 2); (2) to determine if TAGB and structural partitioning within the forest stands differs among forest types (chapter 2); (3) to determine if a quantifiable correlation exists between TAGB measured in this study and modeled estimates derived from the RADAMBRASIL data set (chapter 3); and (4) identify a correlation between TAGB from this study

and RADAMBRASIL commercial volume to be used in a model to predict TAGB. Improved TAGB estimates will increase the accuracy of estimations of carbon pools per unit area and the potential loss of carbon associated with deforestation and biomass burning.

Chapter 2

Total Aboveground Biomass and Structural Characteristics of Amazonian Rainforests in Northern Rondônia, Brazil.

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Keywords: Tropical forest biomass, Tropical forest structure, Brazil, Rondonia, Amazon forests.

Abstract

Tropical rainforests are significant global terrestrial C sinks and deforestation contributes to rising levels of greenhouse gases in the atmosphere. Quantifying the total C pools of tropical forests and levels of C emissions arising from deforestation has been limited by several factors, including accurate calculation of the amount of deforested area, forest fragmentation effects on biomass pools, content and quantity of emissions from fires, and the biomass of intact forests. The total aboveground biomass (TAGB) was measured at 20 sites from the RADAMBRASIL (Departamento National da Producão Mineral, Brazil, (DNPM) 1978) forest inventory of the Brazilian Amazon and quantified. The sites were located in open, dense, and ecotone forest types (as classified in Projeto RADAMBRASIL). TAGB at each site was calculated through the measurement of individual vegetation components. The TAGB of open forest ranged from 288 to 346 Mg ha^{-1} with a mean of 313 Mg ha^{-1}, for dense forest from 298 to 533 Mg ha^{-1} with a mean of 377 Mg ha^{-1}, and for ecotone forests from 298 to 422 Mg ha^{-1} with a mean of 350 Mg ha^{-1}. The average biomass of combined live non-tree components for all 20 sites was 22 Mg ha^{-1}, while combined coarse wood debris (CWD), forest floor (litter/rootmat), and standing dead averaged 38 Mg ha^{-1}, and the TAGB for all live trees averaged 280 Mg ha^{-1}. There was a difference in biomass of trees $\geq$ 10 cm dbh between the open and the dense forest, open forests averaged 239 Mg ha^{-1} and dense forests 307 Mg ha^{-1}. Between sites there was a high degree of variation in the distribution of TAGB among components. In one ecotone forest, non-tree components comprised 41% of the TAGB while it was as low as 12% in a dense

forest site. The mean for non-tree components was 18%, an important result because the non-tree components are often omitted from biomass estimates. Information on the distribution of biomass in tree and non-tree components can improve predictions of carbon released from deforestation processes.

Introduction

Understanding the function of tropical forests as C sinks, and how deforestation effects global carbon cycles and emissions of greenhouse gasses depend on accurate estimates of forest biomass. However, information on total aboveground biomass is scarce for Amazonian forests. Indirect estimates based on commercial volume from forest inventory data collected in the Projeto RADAMBRASIL (Departamento National da Producão Mineral, Brazil, (DNPM) 1978), as well as direct field measurements of individual trees have been utilized to predict total aboveground biomass (TAGB) (Brown and Lugo, 1992; Fearnside, 1989, 1992, 1993; Jordan and Uhl, 1978; Klinge and Herrera, 1978; Russell, 1983; Brown et al., 1995). Estimates for TAGB in the Brazilian Amazon have ranged from 155 to 666 Mg ha^{-1} (Brown et al., 1995; Brown, 1997; Brown and Lugo, 1984,1992; Brown et al.,1989; Fearnside, 1985, 1986, 1987, 1991, 1992a, 1992b, 1993; Kauffman et al.,1995; Klinge et al., 1975; and Ravilla Cardenas, 1987). Differences in TAGB estimates arise in part from the methods and in part due to the heterogeneity of the forests.

Early studies involved destructive sampling to develop predictive models for tree biomass based on dbh or dbh and height. Jordan and Uhl (1978) measured

tree diameters and heights, then harvested and weighed the trees to formulate regression equations for biomass. Based on their models from destructive sampling they reported an average live biomass of 335 Mg ha^{-1} for a "tierra firme" forest in the Venezuelan Amazon. The application of direct and destructive measurement is limited by the time and cost associated with cutting and weighing large trees over a large area of tropical forests. To reduce the dependence on destructive or direct field measurements, commercial volumes derived from forest inventories have been used to estimate total tree biomass (Brown et al., 1989, Brown and Lugo, 1992, Brown, 1997). Although the tierra firme forest sampled by Jordan and Uhl (1978) was considered to be of low stature and biomass for the Amazon, their estimate was almost 100 Mg ha^{-1} more than the mean biomass for Amazonia (227 Mg/ha; Brown and Lugo, 1992) arrived at through models based solely on forest inventories. However, the Brown and Lugo (1992) estimates ignored components of TAGB other than trees $\geq$10 cm dbh. Based on a compilation of results from nine studies for which direct measurements of biomass were made, and the estimates of Brown and Lugo (1992), Fearnside (1992b) gave an average TAGB estimate for the Brazilian Legal Amazon of 335 Mg ha^{-1}. TAGB was quantified for six slashed primary forests by Kauffman et. al. (1995) and Guild et al. (1998). Their biomass estimate ranged from 293 Mg ha^{-1} to 436 Mg ha^{-1} with an average of 362 Mg ha^{-1}. The latter two studies partitioned the biomass into litter, rootmat, dicots, attached foliage and wood debris.

Projeto RADAMBRASIL (DNPM, 1978) included a forest inventory conducted by the Brazilian government to asses the value of forest resources.

RADAMBRASIL inventory data was reported as the volume (m^3 ha^{-1}) of trees $\geq$ 30 cm dbh for each plot and provided a summary of the volume for each forest type. Most of the study plots were one hectare in size (10 x 1000 m). Data from RADAMBRASIL are contained in 50 volumes which cover the forested area of Brazil. The forest type delineation (the classification and area covered by a forest type; i.e. open, dense and ecotone) varied from volume to volume. Based on information from scientists who have interviewed RADAMBRASIL personnel, there are inconsistencies between methods used by field crews and methods of analysis for the different regions and volumes (Nepstad, D; Lucarelli, H personal communication; Fearnside, 1992a, Brown, et al., 1995).

Projeto RADAMBRASIL Vol.16, Folha SC.20 Porto Velho (DNPM, 1978) identified 57 forest sub-types in the state of Rondônia, Brazil. Information from the inventory is currently being used in global models of carbon pools and flux (Dixon et al., 1995; Houghton, 1991; Fearnside, 1992b, 1993, 1997). However, due to the low estimates of TAGB derived from models using the RADAMBRASIL data set compared to data collected in ecological studies, it's use is controversial (Brown and Lugo, 1992; Fearnside, 1992a). The utilization and scaling-up of more detailed measurements to the larger data base of RADAMBRASIL would increase the accuracy of global carbon models essential to predicting climate change. The objectives of this chapter were to quantify TAGB and structure of 20 intact tropical forest sites previously inventoried by Projeto RADAMBRASIL in northern Rondônia, Brazil and to determine if there were differences among forest types.

Study Sites

Study sites were located in the northwestern portion of the state of Rondônia and the southern extreme of Amazonas state, Brazil (Figure 2.1). Forests in this part of Amazonia are representative of forests within the "crescent" of deforestation occurring along the southern and eastern fringe of the Amazon (Skole et. al., 1994). Forests were classified by Projeto RADAMBRASIL as seasonal tropical evergreen forests transitional between evergreen tropical forests and semi deciduous tropical forests (DNPM, Brazil, 1978). Under the Holdridge system, they would be classified as tropical moist forests (Holdridge, 1971). Based on climatological data from Porto Velho (the closest station to the sites) average annual rainfall is ≈ 2300 mm with the majority falling between November and April (DNPM, Brazil, 1978). Mean temperature is 25.2° C (average maximum of 31.1° C, and average minimum of 20.9° C), and average relative humidity is 85% (Departimento Nacional de Meterologia, Brasil, 1992). Soils at the individual sites range from upland red-yellow and yellow oxisols, red-yellow ultisols, to alluvial soils with hydromorphic lateritic, and gley characteristics (DNPM, BRAZIL, 1978). The elevation at the sites ranged from 61 to 310 m.

We sampled 20 sites across 9 forest classifications from Projeto RADAMBRASIL (Vol.16; Folia SC. 20 Porto Velho; Geologia, Geomorfologia, Pedologia, Vegetaçao e Uso Potencial da Terra (RADAMBRASIL); DNPM, Brazil, 1978) (Table 2.1). Each of the 20 sites were forest inventory sites sampled as part of RADAMBRASIL in the early 1970's. Study plots were labeled using the original numbers of the forest inventory plots of the RADAMBRASIL study.

Table 2.1. Forest type classification and location of the RADAMBRASIL forest inventory sites sampled in this study. Region, subregion and formations are those identified by RADAMBRASIL. Locations are ± 100 m.

Forest type - Region	Geomorphic - Subregion	Topographic - Formation	RADAMBRASIL site number and relative location	
Open tropical forest	Amazonian alluvial	Alluvial terraces	225 Lon 63°29'56.1" Lat 8°26'20.9"	226 Lon 63°19'36.9" Lat 8°8'25.5"
	Broken surface of the upper Xigu/Tapajos/Madeira	Submontane rolling hills	70 Lon 65°39'0.6" Lat 9°39'34.9" 74 Lon 63°15'9.9" Lat 9°2'30.1"	75 Lon 63°9'15.1" Lat 9°18'7.4" 76 Lon 63°3'16.4" Lat 9°36'56.0"
		Submontane broken surface	89* Lon 62°15'36.7" Lat 9°41'47.6"	113* Lon 62°20'51.7" Lat 10°11'2.1"
Dense tropical forest	Amazonian alluvial	Alluvial plane, periodically flooded	1* Lon 63°19'38.4" Lat 8°10'58.1"	2* Lon 63°20'14.2" Lat 8°11'23.9"
	Low plates of Amazonia	Rolling low lands	229 Lon 63°59'47.3" Lat 9°1'30.9"	
	Low hills of southern Amazonia	Submontane low hills	24 Lon 63°5'9.5" Lat 10°22'44.7"	25 Lon 63°7'37.9" Lat 10°22'51.3"
	Pre-Cambrian platform cover	Submontane broken surface	43* Lon 65°53'8.8" Lat 9°41'44.4"	44* Lon 63°49'49.9" Lat 9°2'12.4"
Areas of ecological tension (open forest)	Forest /savanna edge	Low land plates	186* Lon 63°58'45.1" Lat 8°33'23.0" 188 Lon 63°57'45.0" Lat 8°23'53.9"	190* Lon 63°31'34.5" Lat 8°35'19.7" 195 Lon 63°36'38.0" Lat 8°42'35.8"
Areas of human influence (open forests)	Platform cover above 600 m	Submontane table lands	218 Lon 65°18'45.5" Lat 10°47'44.7"	

*Due to difficulty obtaining GPS readings under canopy these sites are ± 200 m. Sites 1,2 and 190 may ± 2 km from listed location.

The RADAMBRASIL classification system was based on a hierarchy of ecological regions (i.e., forest types), subregions (i.e., ecological/geomorphology sub-groupings) and formations (i.e., topographic differences). The most coarse resolution classifies our study sites into 3 forest types: (1) "open" (characterized by well spaced individual trees, numerous palms and the presence of vines); (2) "dense" (normally having 3 strata; one of large trees, one of small regenerating trees and one of shrubs and herbaceous material); and (3) "ecotone" (edge forests in contact with savanna and different classes of forest formations) tropical forest. A fourth forest type (represented by 1 plot) classified as anthropogenic disturbance also was identified as open forest. Open forests are the most abundant forest type in Rondônia (DNPM, Brazil, 1978). The 8 subregions (based on the geomorphology of the area) represented in this study ranged from open, Amazonian alluvial terraces to dense southern Amazonian submontane low hills (Table 2.1).

Many of the plots had minor levels of human impact. However the level of disturbance in sample plots did not appear to be greater than that reported at the time of the RADAMBRASIL inventory. For example, subsistence palm and tree harvest for local use and trails used for rubber tapping were reported in the original inventory. Some sites (i.e.;1 ,2, 225, 226 and 218) were located near areas of long term (> 100 yrs.), low density (euro American) settlement and therefore we can assume that there has been ongoing low level impacts on forest structure and composition. Five of the 20 sites had at least 1 stump indicating past selective tree

harvest; site 75 and 229 each contained 3 stumps, site 76 had 2, site 25 had 1, and site 113 had 6 stumps. All the stumps originated > 20 years prior to our study.

Methods

Plot site selection

There were a total of 229 forest inventory sites in Volume 16, Porto Velho, which covered the area of northern Rondônia and Southern Amazonas for Projeto RADAMBRASIL (DNPM, 1978), but we limited ourselves to the northern part of the region due to logistics. Selection of RADAMBRASIL plots for resampling in this study was based on continued existence of the forested plot site (many sites had been deforested) and accessibility. Plots were accessible by a combination of automobile, boat, and hiking. The aforementioned criteria eliminated all but 59 possible sites. The 20 plots selected for use in this study were assumed to be representative of undisturbed Rondonian forests; there was no a priori knowledge of either biomass or structure (other than the RADAMBRASIL classification) of these study sites. Geographical locations of the sites were determined from maps and coordinates provided by D. Skole, University of New Hampshire, and located in the field using a Global Positioning System (GPS) (Table 2.1). We also used a RADAMBRASIL map and satellite photos of the area to assist in plot location. In cases where the area containing the original RADAMBRASIL sites had likely been deforested (i.e. adjacent to a road), we moved our plots to the closest intact forest still within the same forest type, usually a short distance (≈ 200 m) from the road.

Our assumptions that if the data from the inventory RADAMBRASIL are replicable and relevant to estimate TAGB, then the slight differences in relocation should not be an important influence on results.

Total aboveground biomass components

TAGB was estimated by measuring all organic materials above mineral soil. Partitioning of TAGB was based on structural and ecologically significant components and practicality of measurement (Figure 2.2). Trees were separated into 6 diameter classes based on dbh (0-10, 10-30 ,30-50, 50-70, 70-100, 100-200 and 200-300 cm dbh). Tree diameter was measured at 1.37 m above the ground (dbh) or immediately above the tree buttress or stilt roots when present. Palms were divided into three categories (basal palms with no trunks, <10 cm dbh, and ≥ 10 cm dbh) and vines or lianas into two size classes (<10 cm dbh and ≥ 10 cm dbh). Other components included small dicots (plants <1.37 m in height), litter/rootmat (forest floor), standing dead trees and palms, and dead and downed coarse wood debris (CWD), the latter divided into two categories 2.5 - 7.5 cm diameter and ≥ 7.5 cm diameter (diameter of CWD measured at the point of intersection with the transects).

Plot layout

At each site a 75 m x 105 m (0.79 ha) plot was established (Figure 2.3). Two 105 m transects divided the plot into 3 - 25 m x 105 m (0.26 ha) subplots. The diameter for all trees $\geq$ 30 cm dbh was recorded in the entire plot (0.79 ha).

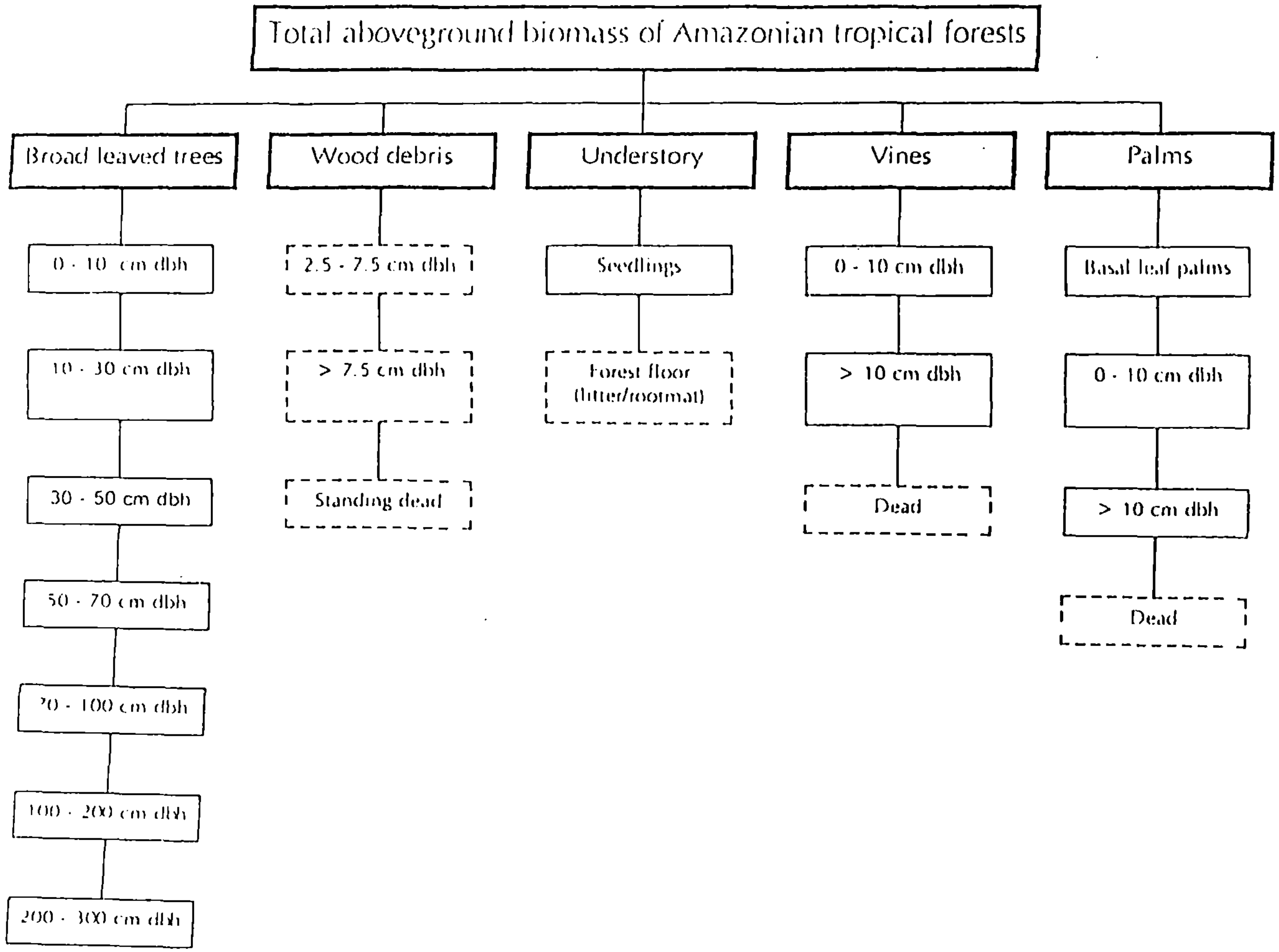

Figure 2.2. Partitioning of total aboveground biomass into components.

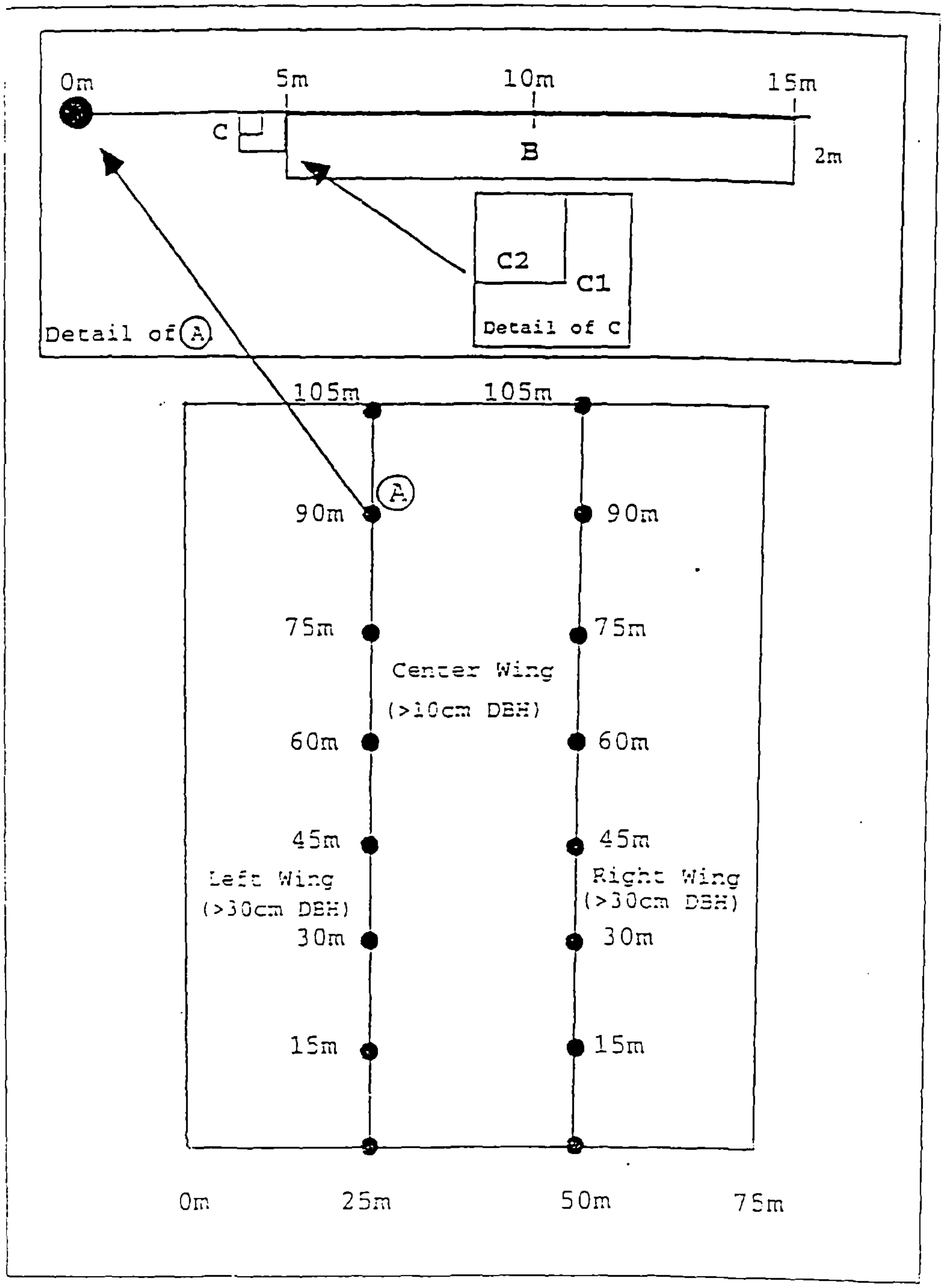

Figure 2.3 Plot layout for total aboveground biomass sampling. Point A indicates the origin of a 15 m coarse wood debris transect. Plot C1 was a 1 x 1 m plot for seedling quantification. C2 was a 0.5 x 0.5 m plot for destructive litter/rootmat samples.

All trees and palms 10 - 30 cm dbh were measured in the center subplot. Along each 105 m transect, we established a planer intersect transect to measure coarse wood debris (CWD) every 15 m (n = 16, 8/transect) (Brown and Rossopoulous 1974; Van Wagoner 1968). At each of the 15 m points along the transect, a 2 x 10 m belt transect was established to measure small trees, vines and palms (> 1.37 m in height, but < 10 cm dbh) and basal leaf palms. At the same 15 m points along the 105 m transect, the biomass of the forest floor was measured in a 50 x 50 cm microplot and density of dicot seedlings in a 1 x 1 m plot was measured.

Procedures

Equations used for calculating each component of the biomass are listed in Table 2.2 and 2.3. Tree height was estimated from a regression equation with tree diameter as the independent variable. Data for the tree height model were collected from 129 trees in Rondônia. Height measurements were made using a range finder and clinometer and dbh was measured with a forestry caliper or dbh tape. Dbh of the trees ranged from 1.5 to 238 cm. Biomass of trees < 5 cm dbh was calculated from equations based on dbh given by Hughes (1997). Biomass of trees ≥ 5 cm dbh were calculated from equations based on dbh given by Higuchi (unpublished, 1997) for Amazonian trees, or the general moist tropical forests equations from Brown et al. (1989).

Biomass of CWD was calculated using the methods of Van Wagner (1964). Transects to measure mass of CWD ≥ 7.5 cm diameter were 15 m in length. CWD 2.5 - 7.5 cm in diameter were measured along 5 m of the 15 m transect. CWD was

Table 2.2. Equations used to determine aboveground biomass of tree components and forest structure. Biomass is expressed in Mg of dry weight.

Parameter	Equation	Source
Trees < 5 cm dbh	$[(\exp(1.0583 \cdot \ln(D^2) + 4.9375)) \cdot 1.143]/10^6$ $R^2 = 0.94$ $N = 66$	Hughes, 1997
Trees 5 cm to 20 cm dbh	$[(\exp(-1.754 + 2.665 \ln(D)) \cdot .604]/10^3$	Higuchi unpublished data, 1997
Trees > 20 cm dbh	$[(\exp(-0.151 + 2.17 \ln(D))) \cdot .604]/10^3$	Higuchi unpublished data, 1997
OR:		
Trees > 5 cm dbh	$\exp(-3.1141 + 0.9719 \ln(D^2 H) + 0.058)$ $R^2 = 0.97$ $N = 168$	Brown, et. al., 1989
Height trees < 20 cm dbh (m)	$[\exp(0.638689 + 0.798819(\ln(D)))] \cdot 1.043785$ $R^2 = 0.85$ $N = 40$	This Study
Height trees > 20 cm dbh (m)	$[19.5873 + \ln(D)] \cdot .999991$ $R^2 = 0.64$ $N = 89$	This Study
Quadratic Stand Diameter (QSD)	$\sqrt{\sum(D^2)/n}$ or $\sqrt{(BA/n) \cdot (4/\pi)}$	
Standing Dead		
Trees < 10 cm dbh	$[\exp((1.1788 \cdot \ln(D^2) + 4.4189) \cdot 1.08191861]/10^6$ $R^2 = 0.96$ $N = 66$	Hughes, 1997
Trees > 10 cm dbh	$(\pi r^2 \cdot H) \cdot Sg$	
Wood debris 2.45 to 7.6 cm dbh	$Sg \cdot ((\pi^2 \cdot N \cdot S \cdot Cs \cdot d^2)/8L) \cdot 10^2$ $Sg = 0.413$ g/cm^3	Van Wagner, 1964
Wood debris > 7.6 cm dbh	$Sg \cdot ((\pi^2 \cdot \Sigma D^2 \cdot S \cdot Cs \cdot d^2)/8L) \cdot 10^2$ Sg sound = 0.492 Sg rotten = 0.342 Sg palm = 0.327	Van Wagner, 1964

Key:
D = dbh (cm); H = height(m); BA = basal area (cm^2); Sg = *specific gravity of wood* (g/cm^3); N = *number of intercepted wood particles*; S = secant of wood particles; Cs = slope correction factor ($\sqrt{1 + (\%slope/100)^2}$; ΣD^2 = Sum of wood particle diameter squared; L = transect length (cm); stem = stem ht. (m); d^2 = quadratic mean diameter of wood particles; r = radius (m)

Table 2.3. Equations used to determine aboveground biomass of non-tree forest components. Biomass is expressed in Mg of dry weight.

Parameter	Equation	Source
Attalea sp Palm > 1.78 m H	$\{[(46.1 * \text{stem H}) - 82.1] + [0.375 * [(46.1 * \text{stem H}) - 82.1]]\}/10^3$ $R^2 = 0.99$ N = 7	Anderson, 1983
Palm (not *Attalea*) > 10 cm dbh	$(4.5 + (7.7(\text{stem H}))/10^3$ $R^2 = 0.90$ N = 25	Frangi and Lugo, 1985
Palm < 10 cm dbh	$[[(\exp(0.9285 * \ln(D^2)) + 5.7236] * 1.0500065]/10^6$ $R^2 = 0.39$ N = 15	Hughes, 1997
Stemless palm	$(\text{Leaves} * 296.54)/10^6$	Cummings this study
Lianas	Base10 $(0.12 + 0.91 \text{ LOG } 10 (\text{BA}))/10^3$ $R^2 = 0.82$ N = 20	Putz, 1983
Dicot seedlings	Seedling Count * Mean Wt (Determined from subsample)/10^6	This study
Forest floor	Wet wt * % dry wt (Determined from subsample)/10^6	This study
Standing dead palm		
Palm < 10 cm dbh	$[(\exp(1.5321 * (\ln D^2) + 3.2758)) * 1.09311496]/10^6$ $R^2 = 0.34$ N = 15	Hughes, 1997
Palm > 10 cm dbh	$(\pi r^2 * H) * Sg/10^6$ Sg = 0.327 g/cm³	

Key:
D = dbh (cm); H = height (m); BA = basal area (cm²); Sg = specific gravity of wood (g/cm³); N = number of intercepted wood particles; S = secant of wood particles; Cs = slope correction factor ($\sqrt{1 + (\%\text{slope}/100)^2}$; ΣD^2 = Sum of wood particle diameter squared; L = transect length (cm); stem = stem ht. (m); d^2 = quadratic mean diamater of wood particles; r = radius (m); Wt = weight in g.

further separated into tree (dicot) wood or palm wood components. The $\geq$7.5 cm diameter class was also separated into sound or rotten classes. One hundred samples for each class were collected in forests near Jamari, Rondonia, to obtain an average wood density. For the 2.5-7.5 cm diameter classes the diameter and angle of 65 individuals along a 100 m transect were measured to calculate the quadratic mean diameter and fuel particle tilt, and to correct for wood particle tilt (Brown and Rousopoulous, 1974). Thereafter, we only counted pieces that intersected the line and used the quadratic mean diameter to calculate biomass.

To calculate forest floor biomass, each sample was initially weighed in the field. Sub-samples were then oven dried to determine the ratio of wet to dry weight. This ratio was then applied to the entire sample to convert from wet to dry weight.

The number of leaves on each basal leaf palm encountered in the 2 x 10 m plot was counted and multiplied by a mean weight per leaf derived from a random sample of 30 basal leaves that were oven dried and weighed. Three equations are necessary to ascertain biomass of palms; biomass of *Attlea* sp. $\geq$ 1.78 m high was calculated using the model by Anderson (1983), that of other palm species $\geq$ 10 cm dbh estimated using the model of Frangi and Lugo (1985), and that of palms < 10 cm dbh calculated using the model of Hughes (1997).

Seedling biomass (< 1.37 m ht.) was based on sub-sample of 50 oven dried plants from which an average weight per seedling was determined. Vine biomass estimates were calculated by the model given by Putz et al., (1983).

Standing dead trees < 10 cm dbh, were calculated from an equation developed by Hughes (1997), while volume of standing dead trees ≥ 10 cm dbh were first calculated then multiplied by the mean value of specific gravity of dead wood (0.413 g/cm^3, the value for sound CWD). Standing dead palm biomass was estimated from Hughes (1997) for palm < 10 cm dbh or from volume multiplied by specific gravity (0.327 g/cm^3) for palms ≥ 10 cm dbh.

Biomass structure as a proportion of tree biomass

To examine the biomass structure of the forest for comparison to other studies both the tree and non-tree components were calculated as a proportion of the aboveground biomass of trees ≥ 10 cm dbh.

Forest structure

Tree density (number of trees ha^{-1}) and basal area (BA; m^2 ha^{-1}) was calculated for each diameter class. Quadratic stand diameter (QSD; cm) is the diameter of a tree of average basal area (formula in Table 2.2.). QSD was calculated for each site based on trees ≥ 10 cm dbh and ≥30 cm dbh. Vine and palm density were derived for stems <10 cm and ≥ 10 cm dbh. Mean TAGB of all vegetative components and TAGB for trees ≥ 10 cm dbh for open, dense and ecotone forest types were compared by ANOVA and a Fishers LSD multiple range test.

Results

Total aboveground biomass

Mean TAGB of open forest (n = 8) was 313 Mg ha^{-1} with a range from 288 to 346 Mg ha^{-1}(Table 2.4). Dense forests (n = 7) ranged from 298 to 534 Mg ha^{-1} with a mean of 377 Mg ha^{-1}. Ecotone forests (n = 4) ranged from 298 to 422 Mg ha^{-1} with an average of 350 Mg ha^{-1}.

The proportion of TAGB composed of trees $\geq$10 cm dbh averaged 77% in open forests, 81% in dense forests, 76% in ecotone forests, and 78% for all plots combined. TAGB (Mg ha^{-1}) for trees $\geq$ 10 cm dbh differed between open and dense forests at the $p = 0.13$ level.

Biomass structure as a proportion of tree biomass

Notable differences among forest types in the structure of biomass as a proportion of aboveground biomass of trees $\geq$10 cm dbh were found in the large trees and palms (Figure 2.4, Appendix A.1). In the open forest trees $\geq$ 70 cm dbh composed 17% of the aboveground biomass of trees $\geq$ 10 cm dbh. For dense forests, those large trees composed 31%, and in ecotone forests, 40%. The proportion of palms was highest in ecotone forests composing 18% of the aboveground biomass of trees $\geq$ 10 cm dbh, while palms in the open and dense forest composed 8% and 6%, respectively. CWD proportion ranged from 3.4% in a dense forest plot to 24.4% in a open forest plot. CWD averaged 13.2%, 11.0% and 9.4% for open dense and ecotone forests respectively, with a mean of 11.6%

Table 2.4. Total aboveground biomass mean for each geomorphic - subregion and topographic - formation. Units are Mg ha⁻¹.

Forest type Region	Geomorphic - Subregion	Topographic - Formation	Plot	TAGB
Open tropical forest	Amazonian alluvial	Alluvial terraces	225	328.8
			226	288.2
	Sub region and Formation Mean ± SE			308.5 ± 20.3
	Broken surface of the upper Xigu/Tapajos/Madeira	Submontane rolling hills	70	345.7
			74	294.7
			75	311.5
			76	310.8
		Formation Mean ± SE		315.7 ± 10.7
		Submontane broken surface	89	299.4
			113	320.9
		Formation Mean ± SE		310.1 ± 10.7
	Sub region Mean ± SE			313.8 ± 12.9
	Region Mean ± SE			312.8 ± 6.7
Dense tropical forest	Amazonian alluvial	Alluvial plane, periodically flooded	1	407.7
			2	319.1
	Sub region and Formation Mean ± SE			363.4 ± 44.3
	Low plates of Amazonia	Rolling low lands	229	299.5
	Low hills of southern Amazonia	Submontane low hills	24	533.8
			25	441.7
	Sub region and Formation Mean ± SE			487.8 ± 46.1
	Pre-Cambrian platform cover	Submontane broken surface	43	298.1
			44	336.4
	Sub region and Formation Mean ± SE			317.3 ± 19.2
	Region Mean ± SE			376.6 ± 33.4
Areas of ecological tension (open forests)	Forest /savanna edge	Low land plates	186	348.3
			188	297.9
			190	422.1
			195	332.6
	Sub region and Formation Mean ± SE			350.2 ± 26.2
	Region Mean ± SE			350.2 ± 26.2
Human Influence	Platform cover above 600 m	Submontane table lands	218	287.3
Grand Mean ± SE				341.2 ± 14.2

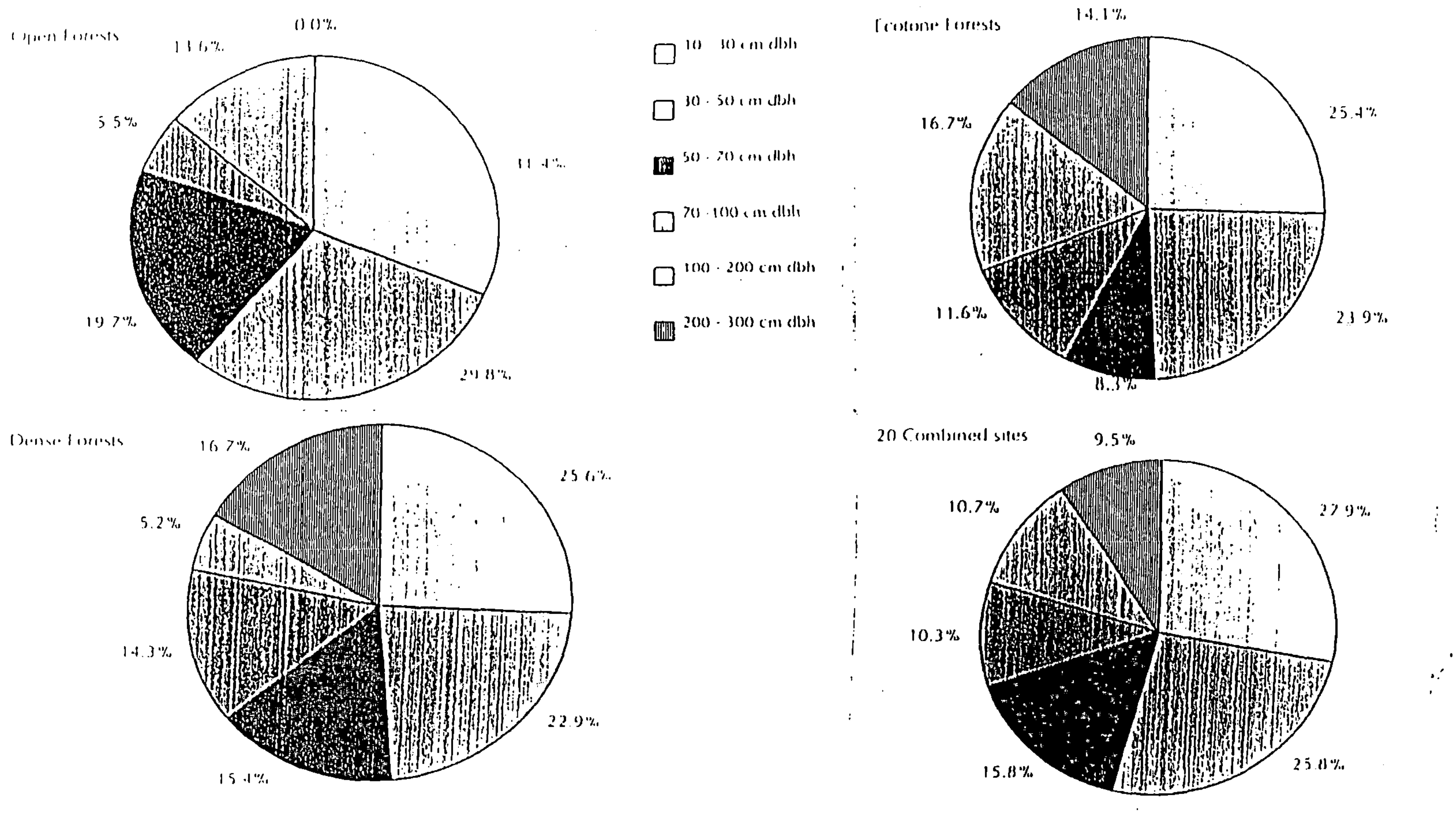

Figure 2.4. Proportion of aboveground biomass of trees > 10 cm dbh in each size class of trees in open, dense and ecotone forest types and for 20 combined sites.

for all plots combined. The forest floor component ranged from a low of 1.3% in a dense forest to a high of 7.1% in a open forest. Forest floor averaged 4.3%, 2.9% and 3.6% for open, dense and ecotone forests respectively, with a mean of 3.4% for all plots combined.

Biomass partitioning among forest components.

Trees

Live trees made up the majority of the TAGB averaging 252 Mg ha^{-1}, 320 Mg ha^{-1} , and 281 Mg ha^{-1} in open, dense, and ecotone forest types respectively (Figure 2.5, Appendix A.2). Comparing biomass of the tree size categories, open and dense forests were similar in average biomass in trees <10 cm dbh (14 Mg ha^{-1}) , 10 to 30 cm dbh (76 and 78 Mg ha^{-1}), 30 to 50 cm dbh (71 and 70 Mg ha^{-1}), and 50 to 70 cm dbh (47 Mg ha^{-1}) (Figure 2.6). The ecotone forests had slightly lower values than open or dense forests for biomass in the diameter classes <50 cm dbh (144 Mg ha^{-1} compared to $\approx$162 Mg ha^{-1} for all classes $<$ 50 cm dbh in open and dense forests) and about half the average biomass in the 50 to 70 cm dbh diameter class (22 Mg ha^{-1} compared to 47 Mg ha^{-1} in open and dense forests). The open forest diameter classes $\geq$ 70 cm dbh contained lower biomass than the same diameter classes for dense or ecotone forests, 45 Mg ha compared to 111 and 114 Mg ha^{-1} respectively (Figure 2.6, Appendix A.2).

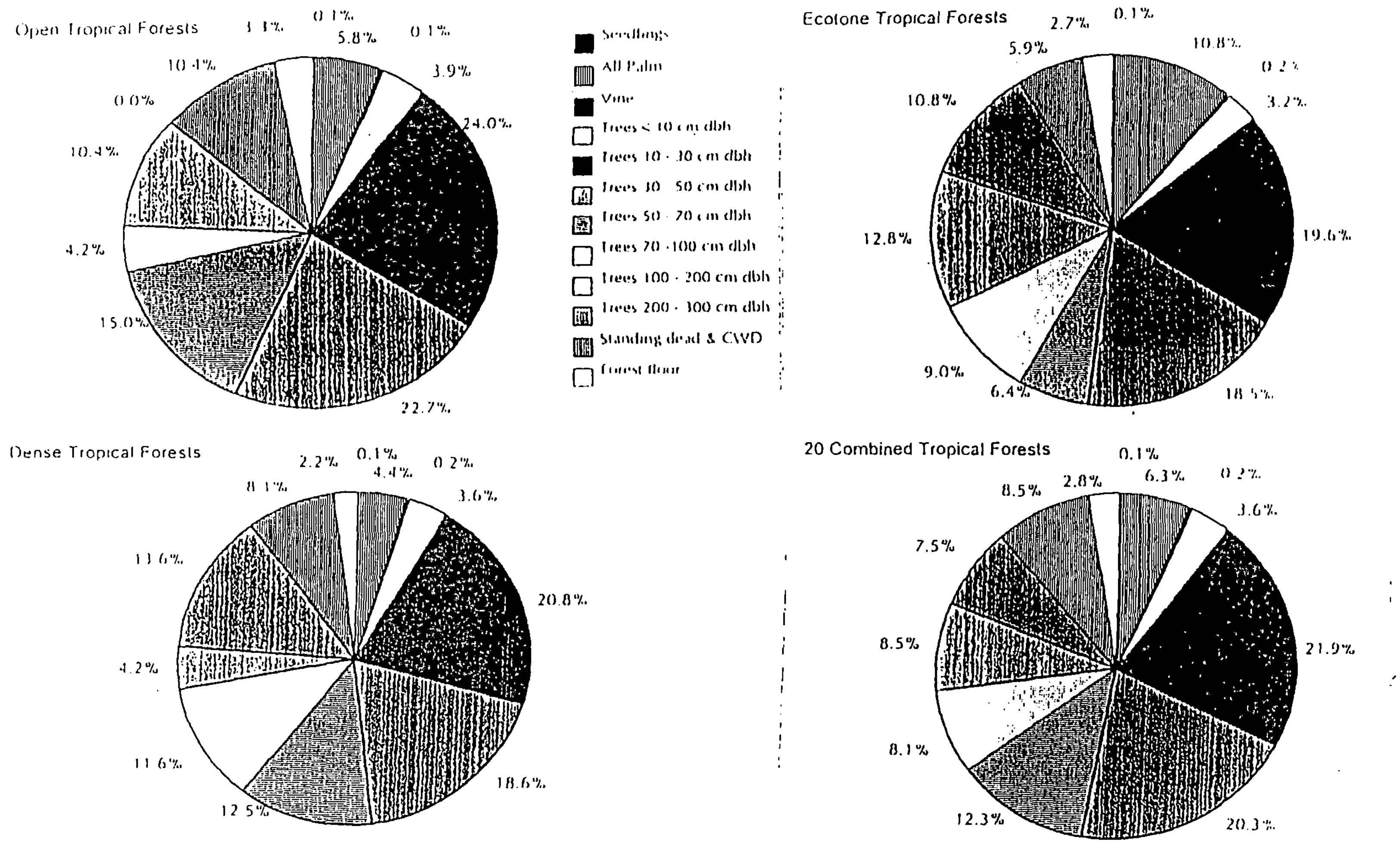

Figure 2.5. Proportion of total aboveground biomass in each component for open, dense and ecotone forest types and for the 20 combined sites.

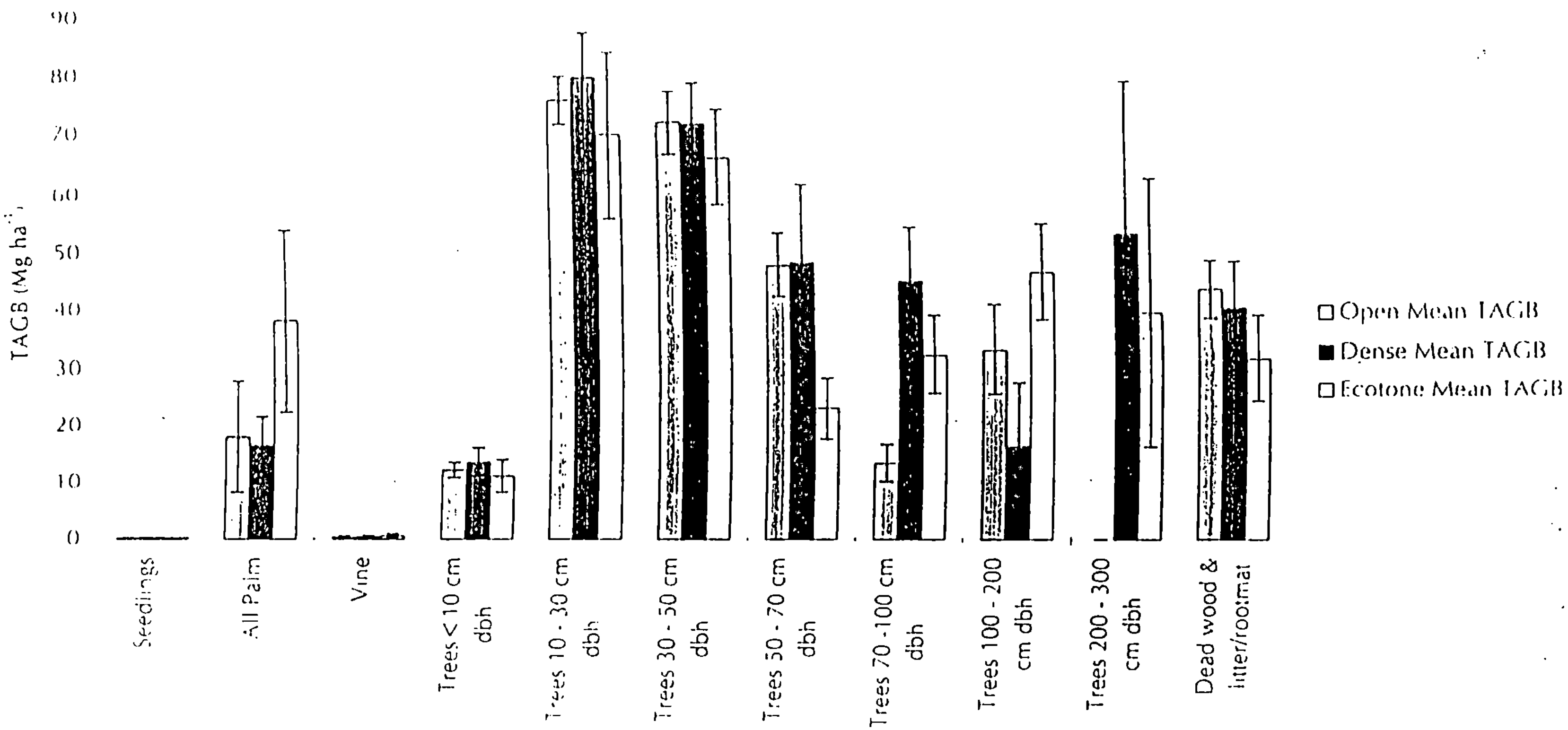

Figure 2.6. Distribution of total aboveground biomass in components for open, dense and ecotone forest types

Non-tree components

Biomass of live non-tree components (seedlings, palms, and vines) was ≈ 18 Mg ha^{-1} in both open and dense forest types, and 39 Mg ha^{-1} in ecotone forests (Figure 2.6, Appendix A.3). However, biomass of non-tree components was highly variable within a given forest type, ranging from 4 to 95 Mg ha^{-1} in open forests, 3 to 39 Mg ha^{-1} in dense forests, and 1 to 74 Mg ha^{-1} in ecotone forests. If a single plot (225) in the open forest was excluded the average for open forests would drop to 7 Mg ha^{-1}, or less than half that of the dense forests. Plot 225 had a high biomass value for non-tree live vegetation due to the biomass of large diameter palms. The large non-tree biomass of ecotone forests was also primarily the result of biomass of large palms ($\geq$ 10 cm dbh). Vines and other understory vegetation contributed minimally to the TAGB (a range of 0 to 3 Mg ha^{-1} over all forest types).

In general, CWD, standing dead, and litter along with the rootmat composed an equal or larger proportion of the TAGB than non-tree live vegetation (Figure 2.5 and 2.6). The forest floor component was composed of litter, small wood debris (<2.5 cm diameter), and rootmat. Rootmat contained a large amount of decomposing organic matter as well as live roots and was not as well developed as those reported by Kauffman et al. (1988).

CWD and standing dead (palms, vines and trees), averaged 32 Mg ha^{-1} in open forests, 30 Mg ha^{-1} in dense forests, and 28 Mg ha^{-1} in ecotone forests (Appendix A.4). The largest contributor was CWD with a mean for all plots of 29

Mg ha^{-1}. Mass of the forest floor was 9 Mg ha^{-1}. The remaining components of standing dead palms, trees and vines ranged from of 0 to 1 Mg ha^{-1}.

Differences in forest structure among forest types

Density

The widest range in density of trees $\geq$ 10 cm dbh within forest type occurred in the open and ecotone forests which ranged from 291 to 527 trees ha^{-1} and 223 to 487 trees ha^{-1} respectively, while the dense forests had a narrow range of 402 to 533 trees ha^{-1} (Figure 2.7, Appendix A.5). Average density of live trees < 10 cm dbh ha^{-1} differed by 25% between the open forest ($\approx$ 7500 ha^{-1}), dense forest ($\approx$ 5800 ha^{-1}) and ecotone forests ($\approx$ 4900 ha^{-1}), but plots within a given forest type varied widely (from $\approx$ 2000 to 9000 ha^{-1} in each forest type; Figure 2.7, Appendix 2.5).

Breaking density into size classes, in the 50 to 70 cm dbh class for live trees, the ecotone forest averaged about half the number of trees ha^{-1} as the open and dense forests (6 ha^{-1} compared to 13 ha^{-1}). Density of large trees ($\geq$ 70 cm dbh) averaged $\approx$4 ha^{-1} in the open forest and $\approx$7 ha^{-1} in the dense and ecotone forest. Open forests averaged fewer trees ha^{-1} in the 70 to 200 cm dbh classes (4 ha^{-1} compared to 6 ha^{-1}) and no trees were found in the largest diameter class ($\geq$ 200 cm dbh).

The density of standing dead trees < 10 cm dbh was similar among forest types ($\approx$80 ha^{-1} ; Appendix A.5). Dead trees 10 to 30 cm dbh varied slightly among

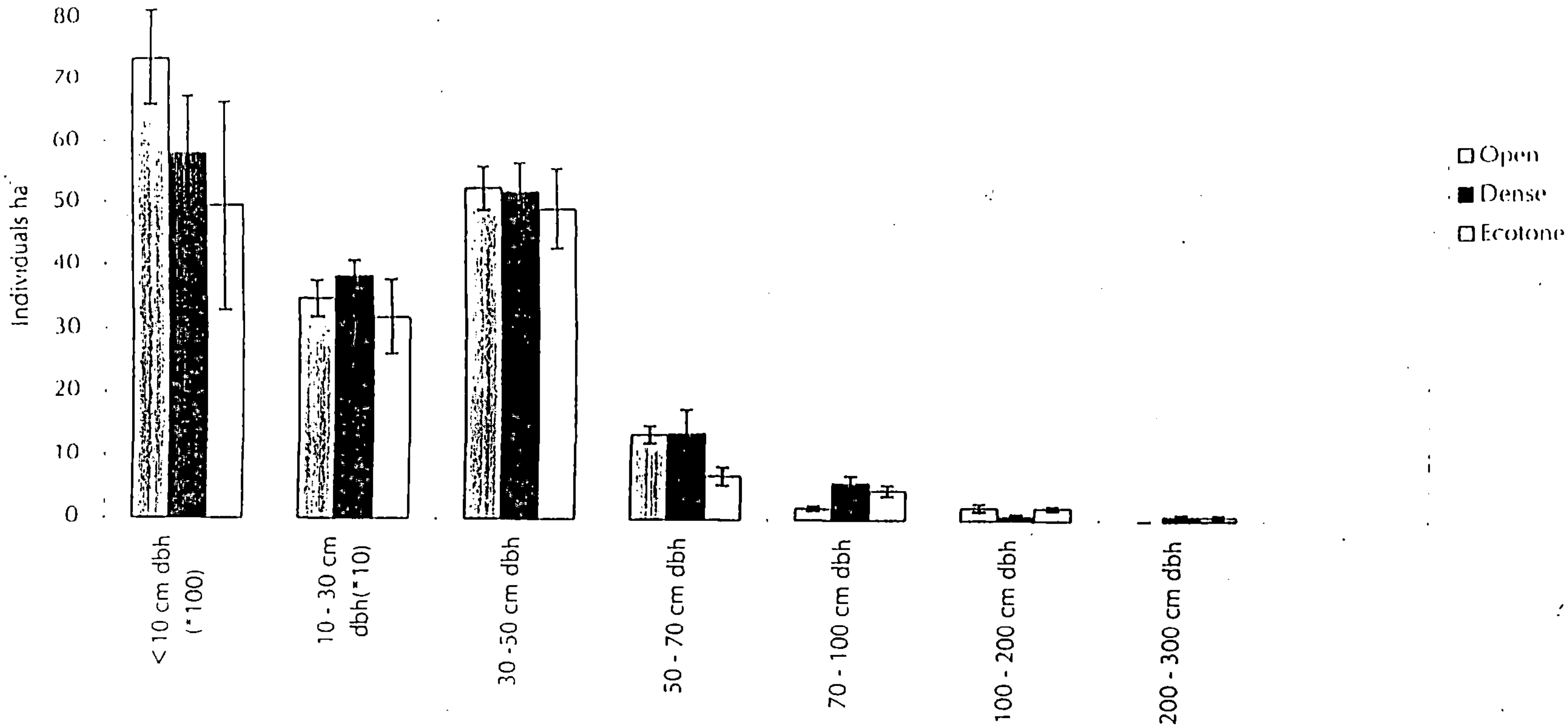

Figure 2.7. Density of trees in each size class for open, dense and ecotone forest types.

the forest types with 27 ha^{-1}, 19 ha^{-1}, and 13 ha^{-1} for open, dense, and ecotone forests respectively. The density of standing dead trees > 30 cm dbh was similar in dense and ecotone forests at 6 ha^{-1} and 5 ha^{-1} while open forest had 10 ha^{-1}.

Density of palms and vines followed a pattern similar to their biomass (Figure 2.8, Appendix 2.6). The most dramatic differences were in the palms $\geq$ 10 cm dbh. Open forest averaged approximately two thirds the number of palms $\geq$ 10 cm dbh ha^{-1} as the dense and ecotone forests (60 ha^{-1} compared to 97 and 107 ha^{-1}, respectively) (Table 2.5). The open and dense forests had about one third of the number of palms < 10 cm dbh ha^{-1} than the ecotone forest (203 and 196 ha^{-1} compared to 633 ha^{-1}). Densities of seedlings and vines < 10 cm dbh were similar among forest types. Vines > 10 cm dbh were similar in dense and ecotone forest but lower in number in the open forests (5 ha^{-1} compared to 1 ha^{-1}). Basal leaf palms were similar in density in open and ecotone forests ($\approx$750 ha^{-1}) but lower in dense forests (443 ha^{-1}).

Basal area and quadratic stand diameter

The total BA ranged from 19 to 26 m^2 ha^{-1} in open, 23 to 37 m^2 ha^{-1} in dense and 15 to 34 m^2 ha^{-1} in ecotone forests. The average total basal area of each forest type did not differ by more than 5 m^2 ha^{-1} (average 24 m^2 ha^{-1}, 28 m^2 ha^{-1} and 24 m^2 ha^{-1} for open dense and ecotone forests respectively; Figure 2.9, Appendix A.7). The difference in average basal area is equivalent to that of one very large tree ha^{-1} ($\geq$ 200 cm dbh). Likewise QSDs were only slightly different between forest types. The mean QSD of open forests was 25 cm; dense forests

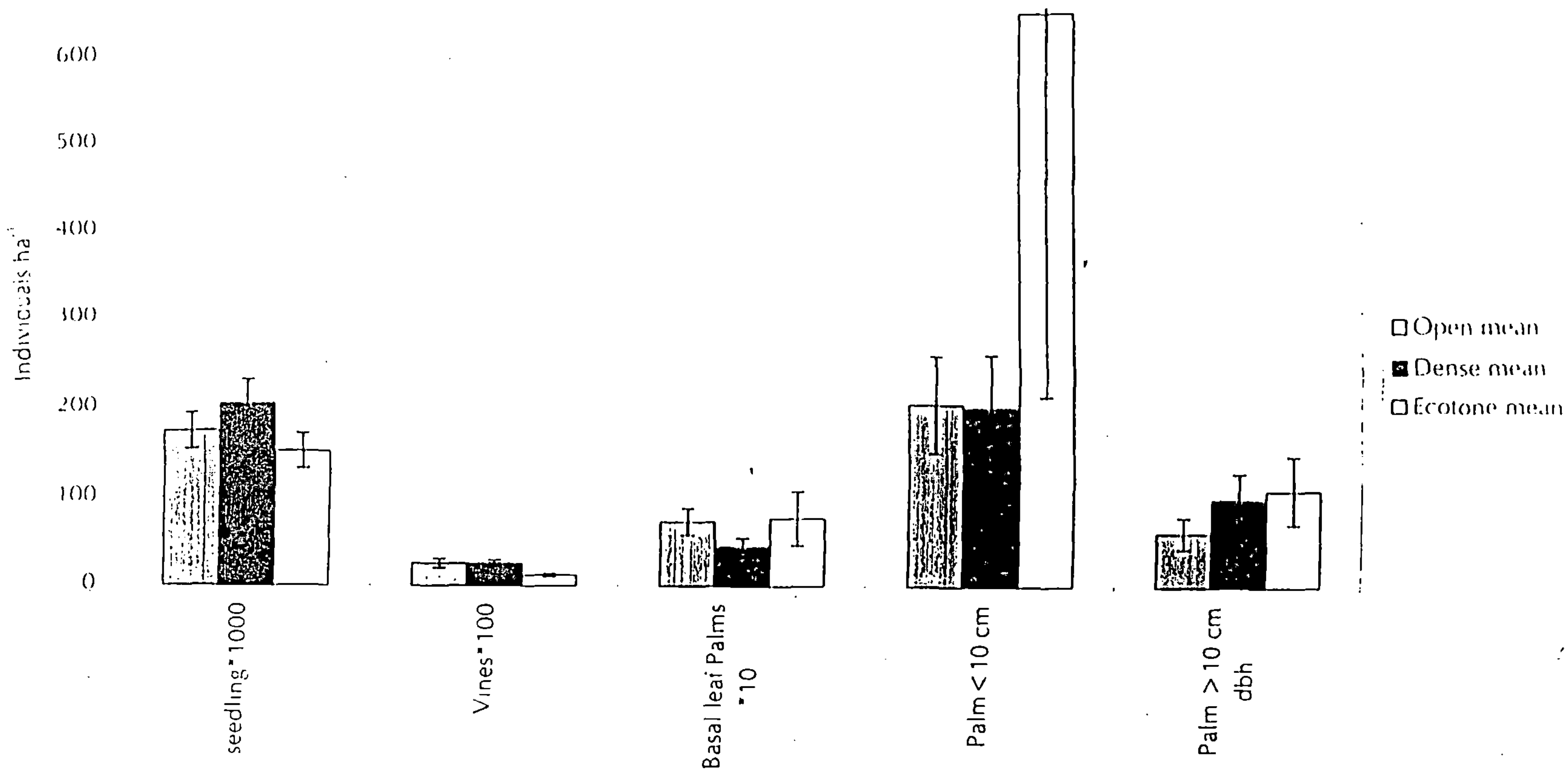

Figure 2.8. Density of non-tree components for open, dense and ecotone forest types.

Table 2.5. Palm Structure (> 10 cm dbh) in 20 RADAMBRASIL forest inventory sites. Values are means for each site.

Forest type - Region	Geomorphic - Subregion	plot	Palm biomass (Mg ha-1)	Hieght (m)	Density (palm ha⁻¹)	Diameter at breast hieght (cm)		*Attalea sp.* Dominant (Yes/no)?
						Attalea sp.	Other sp.	
Open tropical forest	Amazon alluvial	225	92.3	11.2	171	30	24	y
		226	1.9	8.5	15	33	19	n
	Broken surface of the Upper Xingu / Tapajos / Madeira	70	5.6	7.8	107	30	13	y
		74	2.5	16.0	27	nd	nd	n
		75	0.0	nd	11	nd	13	n
		76	7.3	7.9	65	38	14	y
		89	6.8	6.7	23	40	0	y
		113	8.3	8.0	61	37	19	y
	Mean		15.6 ± 11.0	9.4 ± 1.2	60 ± 20	35 ± 6	14 ± 3	
Dense tropical forest	Amazon alluvial	1	10.4	8.9	114	34	27	n
		2	7.3	5.4	160	0	26	n
	Low plates	229	0.4	13.0	4	0	10	n
	Low hills of Southern Amz.	24	22.7	10.6	42	22	0	y
		25	24.5	10.0	130	35	18	n
	Pre-Cambrian platform cover	43	36.4	8.4	202	28	14	n
		44	5.5	15.9	30	28	13	n
	Mean		15.3 ± 4.9	10.3 ± 1.3	97 ± 28	29 ± 5	18 ± 4	
Areas of ecological tension	Savanna / forest edge	281	46.0	9.3	130	31	11	y
		188	71.5	7.9	187	32	29	y
		190	0.8	13.5	8	0	17	n
		195	23.8	7.5	103	31	26	y
	Mean		35.5 ± 15.1	9.5 ± 1.4	107 ± 37	31 ± 7	20 ± 4	
Others	Anthropogenic	218	21.2	9.0	57	26	16	
Grand mean			19.8 ± 5.6	9.8 ± 0.7	82 ± 14	31 ± 3	18 ± 2	

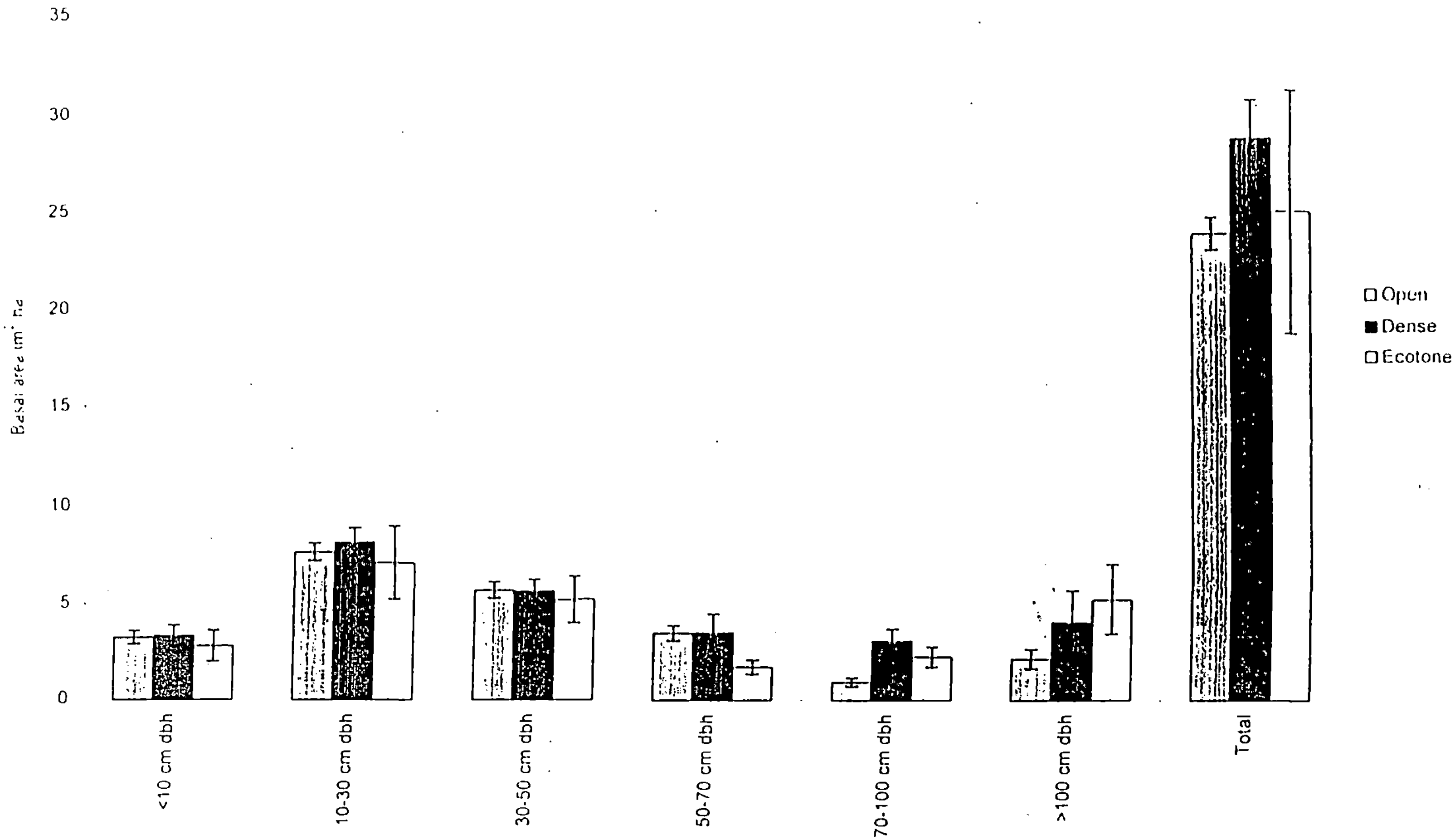

Figure 2.9. Basal area of each size class of trees and the total for open, dense and ecotone forest types.

was 27 cm, and ecotone forests 27 cm (trees ≥ 10 cm dbh; Appendix A.8). The mean QSDs of trees ≥ 30 cm dbh for dense and ecotone forests were higher than that of open forests (48 cm in open forests, 54 cm in dense forests and 55 cm in ecotone forests).

Vertical structure

The dense and ecotone forests had the highest canopy due to the presence of a few very large trees (>200 cm dbh). The tallest trees in the open forest (100 to 200 cm dbh) averaged 44 m in height. In the dense and ecotone forests the tallest trees (200 to 300 cm dbh) were ≈ 52 m in height. The average height for the 70 to 100 cm dbh size class was 39 m over all sites. The presence of emergent trees was noticeable in the dense and ecotone forest types with dominant trees in the 200-300 cm dbh class ranging from 5 to 14 meters taller than the average of the next tallest trees in the plot.

Discussion

Total aboveground biomass differences among forest types in Northern Rondônia, Brazil

Evidence of past harvest did not appear to influence TAGB to a significant degree. Mean TAGB was not significantly different ($p = 0.8$) between plots with and without cut trees. The mean TAGB in open forests without the plots containing harvested trees was 10 Mg ha^{-1} lower than that of the plots containing harvested

trees, whereas the mean TAGB in dense forests without the harvested plots was 8 Mg ha^{-1} higher than that of the plots with harvested trees.

As would be expected in areas with abundant precipitation there is no noticeable pattern in biomass associated with a north to south gradient of decreasing rainfall over the area included in this study. Plots were located between 8° and 11° latitude and 62° to 66° longitude, the effects of decreasing rainfall would likely be pronounced in southern Rondônia. Over the area covered in our study other site conditions appear to have a greater influence than precipitation on TAGB.

The range in TAGB of open forests was much smaller than that found in the dense or ecotone forest types (Figure 2.10). All 3 major forest types in this study had similar values for sites at the low end of the TAGB range (≈ 294 Mg ha^{-1}; Table 2.4). The highest biomass values were in the 2 dense forest hill sites and accounted for much of the variability in the dense forest type. In ecotone forest there was no clear relationship of TAGB to geomorphology. Site to site variability within forest types and subregions may be as much or greater than the variability among forest types. This suggest that for the purpose of estimating TAGB in Rondônia, the scale of geomorphology (sub-regions) within forest type (region) may be more appropriate than the coarser scale of forest type alone. To test this hypothesis adequately would require data collection in each sub-region. The problem of deriving better estimations of TAGB based on forest classification systems used in RADAMBRASIL may be overcome by resampling more sites.

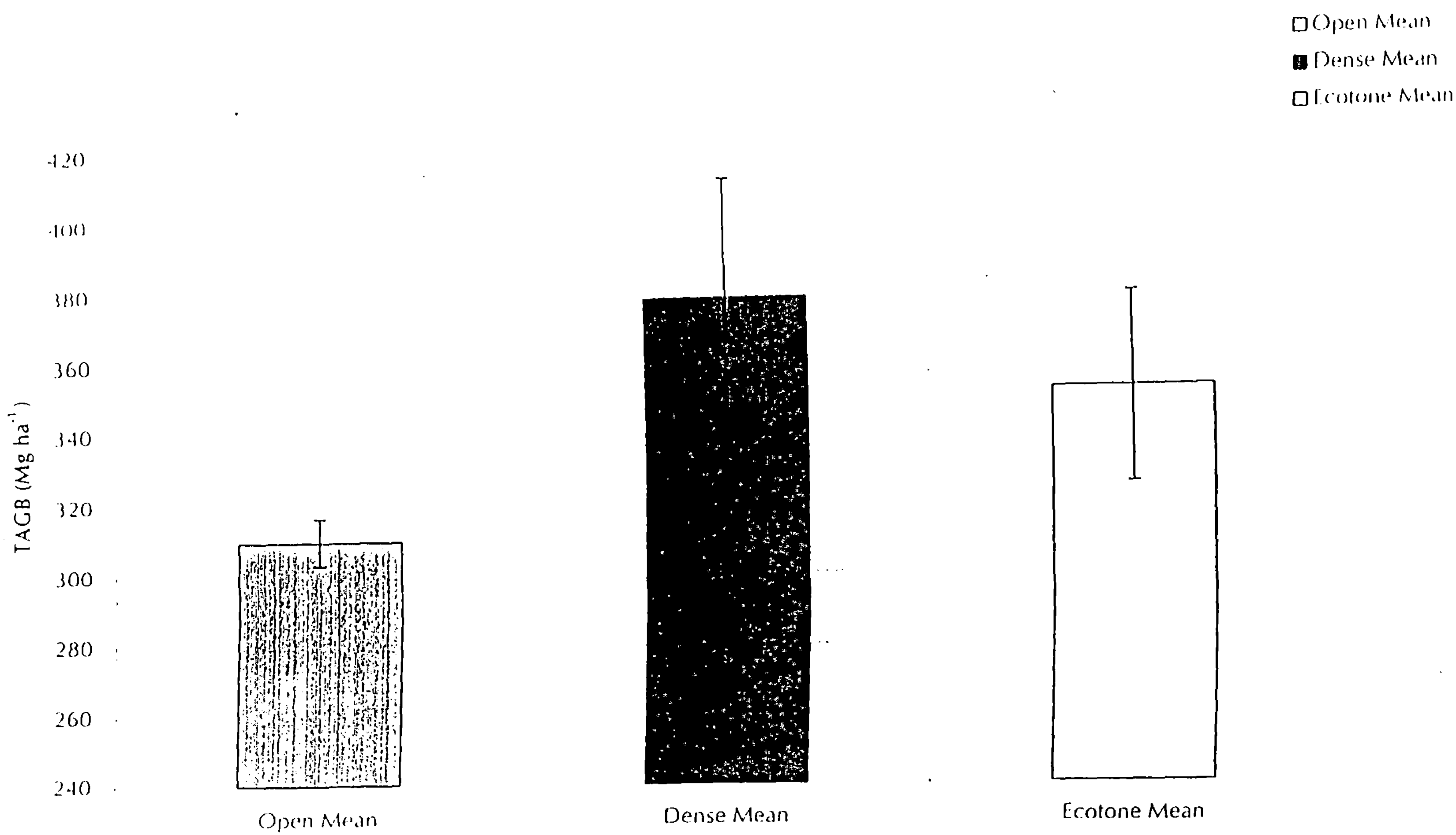

Figure 2.10. Total aboveground biomass for open, dense and ecotone forest types.

Brown, S. et al, (1989) and Brown and Lugo (1992) suggested that field estimates resulted in higher TAGB because of a bias by researchers and/or foresters in site selection. In contrast Brown, I.F., et al. (1995) found that biomass from a site selected based on its appearance as a "good" forest yielded a lower biomass than sites selected without regard to forest structure. They attributed the inability to see more than 30 to 40 m into a forest with the failure of subjective selection to result in biased high biomass estimates. We found the same to be true in the forests we resampled. It would be extremely difficult, if not impossible, to determine what the end of a 105 m transect will look like based on the view from one end. Visual distances > 15 m are rare in intact forests.

The mean of biomass estimates in our study agrees with many others. The live aboveground biomass in open forests of our study (Appendix A.2 and A.3) averaged 270 Mg ha^{-1} compared to 285 Mg ha^{-1} given in Brown, I.F., et al. (1995). TAGB for dense forests in our study averaged 376 Mg ha^{-1} and is comparable to 361 Mg ha^{-1} given by Fearnside (1985) and 352 Mg ha^{-1} reported in Brown, I.F., et al. (1995, from C estimates by the Intergovernmental panel on Climate Change, 1992, p 89). Fearnside's (1992b) area weighted mean TAGB estimates derived from modified forest inventory data for forest types in Rondônia are comparable to ours for open forests (316 Mg ha^{-1} or +1%) and ecotone forest (330 Mg ha^{-1} or -6%) but substantially lower for dense forests (310 Mg ha^{-1} or - 18%). Previous direct measurements of TAGB from dense forests in the Legal Amazon have ranged from 206 Mg ha to 437 Mg ha^{-1} (Revilla Cardinas, 1986 and 1987) and average 313 Mg ha^{-1} (calculated from Revilla Cardinas, 1986, 1987 and 1988; Klinge et al.,1975;

Martinelli et al., 1988 as reported in Fearnside, 1992b). This was substantially lower (by 64 Mg ha^{-1} or -17%) than our average for dense forests (average 377 Mg ha^{-1}, range 298 - 533 Mg ha^{-1}). The average for open forests from direct measurement is 258 Mg ha^{-1} (Revilla Cardinas, 1986 and 1987) also lower (by 55 Mg ha^{-1} or -18%) than our average for open forests (313 Mg ha^{-1}, range 288 - 346 Mg ha^{-1}). Kauffman et al. (1995) found TAGB in slashed primary forests to be 292 and 435 Mg ha^{-1} in 2 dense forests and 290 and 361 Mg ha^{-1} in 2 open forests in the Brazilian Amazon. These differences explain some of the variability in TAGB estimates from small studies; examined in isolation they appear to give widely disparate TAGB but considered together they cover the range of biomass present in Amazonian forest types. In this study the average minimum TAGB value for plots in open, closed and ecotone forests was 294 $\pm$ 6 Mg ha^{-1}.

In contrast, in this study the maximum TAGB in the open forest plots was 346 Mg ha^{-1} , while dense and ecotone forest plots have the potential to be as high as 534 and 422 Mg ha^{-1} respectively. Although not measured in this study we observed numerous ecotone forests that were lower in biomass than the RADAMBRASIL sites represented by our sample plots.

Biomass partitioning among forest components

Trees

There were slight differences among forest types in the way biomass was partitioned among components (Figure 2.6), however the site variability within

forest types was sometimes greater than among forest types (Appendix A.3). The mean biomass for all trees < 50 cm dbh was similar among the 3 major forest types (Figure 2.6). Size classes 10 to 50 cm dbh contributed the highest proportion of TAGB in all 3 major forest types (47%, 42%, and 38% of TAGB in open, dense, and ecotone forests respectively, Figure 2.5). Combined biomass of trees ≥ 10 cm dbh was ≈ 80% of TAGB for the forest types combined (Figure 2.5).

Gillespie et al., (1992) estimated that trees in the 10 to 35 cm dbh class constitute 23 to 40 % of aboveground biomass for trees ≥ 10 cm dbh in Venezuela. Our study showed trees from the 10 to 30 cm dbh class made up 15 to 43 % of the aboveground biomass for trees ≥ 10 cm dbh (Figure 2.4, Appendix A.1). This illustrates the important contribution of small trees to TAGB, a size class the RADAMBRASIL inventory did not measure.

Although among forest types there were differences in total tree biomass, the way the biomass was distributed among trees ≥ 30 cm dbh as compared to aboveground biomass of trees ≥ 10 cm dbh was similar. The aboveground biomass of trees ≥ 30 cm dbh composed 68%, 72%, and 75% of the aboveground biomass of trees ≥ 10 cm dbh in open, dense, and ecotone forests respectively (Figure 2.4). Brown and Lugo (1992) assumed that in open forests the fraction of the total volume of trees ≥ 10 cm dbh represented by trees ≥ 30 cm dbh would be more than 10% lower than that of dense forests. If volume can be assumed to be directly correlated to biomass, then the assumption of Brown and Lugo (1992) doesn't hold for sites in our study where the fractions of the biomass were within 5% of each other.

The greatest variation in biomass distribution among forest types was in the dbh classes > 50 cm. The dense forest had the greatest amount of TAGB in the largest size classes (mean 158 Mg ha^{-1}, ranging from 47 to 305 Mg ha^{-1}), followed by the ecotone forests (mean 137 Mg ha^{-1}, ranging from 78 to 208 Mg ha^{-1}), and open forests (mean 92 Mg ha^{-1}, ranging from 58 to 139 Mg ha^{-1}; Appendix 2.2). In terms of proportional distribution of biomass (structure), the greatest difference was in the trees ≥ 70 cm dbh, which made up 18%, 31%, and 41% of the aboveground biomass of trees > 10 cm dbh in open, dense and ecotone forests respectively (Figure 2.4). In terms of TAGB large trees (≥ 70 cm dbh) made up an average of 15% in open forests, 29% in dense forests and 33 % in ecotone forests, or 24 % of the combined 20 sites (Figure 2.5). This is consistent with estimates by Brown and Lugo (1992) that large trees compose < 40% of TAGB in Amazon forests.

Five sites out of 20 had no trees in diameter classes ≥ 100 cm dbh. It should be noted that the 5 sites without trees ≥ 100 cm dbh showed no evidence of tree removal. Of the 5 plots without very large trees, 2 were in the open / alluvial forest type, 2 were in the dense / pre-Cambrian forest type, and the other was in dense / alluvial forest. The lack of very large trees may indicate a limitation for growth at the site or may indicate simply limitations of the plot size. However, the plot size used in our study for trees ≥ 30 cm dbh (0.79 ha) was well above the minimum plot size (0.25 ha) recommended by Brown, I.F., et al. (1995).

Density of large trees (calculated as the number of trees ≥ 70 cm dbh divided by the total area sampled for each of the three forest types) was 3.8, 6.7,

and 7.0 trees ha^{-1} in open, dense and ecotone forests respectively. Densities of very large trees ($\geq$ 100 cm dbh) were 2.1, 1.5, and 2.5 trees ha^{-1} while those $\geq$ 200 cm dbh have densities of 0.0, 0.7, and 0.6 trees ha^{-1} for open, dense and ecotone forest types respectively. The greatest difference between the open forest type and the other 2 types was the absence of the largest trees $\geq$ 200 cm dbh in the former (There were none in 8 open forest sites totaling 6.30 ha). Forty five percent of the 11 sites in dense or ecotone forests (7 sites totaling 5.51 ha and 4 sites totaling 3.15 ha respectively) had trees $\geq$ 200 cm dbh. Jordan and Uhl (1978) suggest that the absence of very large trees in the tierra firme forest of the Venezuelan Amazon may be due not only to low soil nutrients but also to mortality of slow growing trees before they can attain larger size. Our study lends some support to the Jordan and Uhl hypothesis, in that open forests had 4 times more biomass in standing dead trees from all size classes than dense forests (that represents a very small biomass difference of 0.11 compared to 0.03 Mg ha^{-1}).

Non-tree components

Non-tree aboveground biomass had a wide range in the open and ecotone forest of 91 and 73 Mg ha^{-1}, respectively, between the lowest and highest values while, dense forest had a narrow range of 36 Mg ha^{-1} between the highest and lowest values. Palms were a major contributor to the non-tree biomass, and there was large variation in their abundance in both open and ecotone forests (Figure 2.5, Table 2.5). The palm contribution to TAGB ($\approx$ 6%) over all 20 sites (Figure 2.5) is higher than the 1.3 % calculated from Jordan and Uhl (1978) in "tierre firme"

forests in the Amazon basin of Venezuela. Fearnside (1992) used a factor of 3.5% of aboveground biomass of trees ≥ 10 cm dbh to account for palm biomass in Amazonian forests. The mean percent that palm biomass comprised of aboveground biomass for trees ≥ 10 cm dbh in our 20 sites was 9.3% (Figure 2.4, Appendix A.1). We assumed that palms ≥ 10 cm dbh would have a greater density and biomass in open and ecotone forest types than in dense forests because RADAMBRASIL (DNPM, 1978) described open forests as having enclaves of palms, however, this turned out not to be prevalent in our sites. Large palm biomass in open forests was highly variable from 0.09 to 92.32 Mg ha^{-1} while, dense forests were less variable from 0.04 to 36.42 Mg ha^{-1} yet both forests averaged approximately the same biomass (15 Mg ha^{-1} in each). Ecotone forests averaged twice the palm biomass of open and dense forests (35 Mg ha^{-1}), but was also highly variable (from 0.80 to 71.47 Mg ha^{-1}). The density of palms was lower in open forests (60 ha^{-1}) compared to dense and ecotone forests (97 and 107 ha^{-1}, Table 2.5). The potential discrepancy between density and biomass of palms among the forest types is explained by individual site characteristics (Table 2.5). In general, the palms in the open forest were larger and had more biomass per individual than those in dense forests. *Attelea spp.*, a robust palm with a thick stem and a high biomass to height ratio, was dominant in 5 of the 8 sampled areas in open forests, 3 of the 4 sampled areas in ecotone forests, and only 1 of the 7 sampled areas in dense forests. Other palm species present in the plots may attain a greater height but tend to have less robust stems than *Attelea spp.*, averaging 18 cm dbh versus 31 cm dbh. A non-specific regression was used in calculating palms ≥ 10 cm dbh

other than *Attelea spp.* (for which a specific regression was available; Anderson, 1983. Table 2.3), because of this non-specificity, variations in specific gravity, leaf biomass, or structure (other than height) would not be taken into account thereby reducing the accuracy of the biomass estimate.

Seedlings and vines comprised a minor proportion of the TAGB in our study sites (average < 0.4% of aboveground biomass for trees $\geq$ 10 cm dbh, with the maximum combined value for any of the forests sites at 1.27% (Figure 2.4, Appendix A.1). Fearnside (1992a) used a factor of 4.25 % of aboveground biomass of trees $\geq$ 10 cm dbh for vines and a factor of 0.21% for other non-tree components (Fearnside's factor is based on an average from direct measurement studies by Revilla Cardenas, 1986, 1987, and 1988, Klinge et al., 1975, Fearnside et al., 1983, and Martinelli et al., 1988). Klinge (Unpublished ms, reported in Jordan and Uhl, 1978) found vines to be only 0.3% of the biomass in a lowland Amazon forest in Venezuela.

Dead wood debris (from palms, vines and trees both standing and on the forest floor) combined with litter and rootmat in the forest floor composed the largest non-tree component of the TAGB in open and dense forests (Figure 2.5 and 2.6), with a grand mean of 11.3% of TAGB, and a range from ≈ 17 Mg ha^{-1} in 2 dense, alluvial forests to 73 Mg ha^{-1} in 1 open, broken surface forest site. The greatest proportion of the combined biomass came from CWD (74%), followed by the combined litter and rootmat (25%) and only a slight contribution from standing dead (0.7%).

In this study, 5 plots were observed to have continuous rootmat, 7 had discontinuous and sparse rootmat , 4 had no rootmat and there was no notation on the remaining 4. Average biomass of the combined litter and rootmat were 13.8, 7.9, 5.3 and 9.2 Mg ha^{-1} for continuous, sparse, no rootmat and those without data respectively. Overall, the combined litter and rootmat averaged 9.6 Mg ha^{-1} for all 20 plots. The forest floor in plots with substantial rootmat were usually observed to also have a substantial litter layer. Although the roots in the rootmat are live they are woven through a layer of decomposing organic matter. The rootmat was included with litter in our study for three reasons: (1) it was biomass above the mineral soil surface; (2) it was impossible to separate in the field and, (3) it would be susceptible to the effects of deforestation. For example, Kauffman et al. (1995) found that biomass burning for conversion to pasture resulted in the consumption of > 99% of the litter and rootmat layers combined.

Large wood (CWD) averaged 29 Mg ha^{-1} or 8.4 % of the TAGB in our study sites and ranged from 3 to 17% (Figure 2.6). Combined CWD and forest floor from our study averaged 38 Mg ha^{-1} ranging from 17 - 72 Mg ha^{-1} . Uhl and Kauffman (1990) found litter and CWD to be 56 Mg ha^{-1} for a dense forest in Para, Brazil. Kauffman et al. (1988) found the mass of forest floor and CWD combined to be 64 and 107 Mg ha^{-1} respectively for species rich and species dominant tierra firme forests in the Venezuelan Amazon. The combined average percentage of litter and rootmat for other Amazonian forests (compiled from references; Revilla Cardenas, 1986, 1987, and 1988 and Martinelli et al., 1988) was 5% of the live aboveground biomass. Litter and rootmat comprised 4% to 8% of the TAGB in 4 slashed forests

from Para and Rondonia (Kauffman et al., 1995). Those values from other studies are comparable to the grand mean for this study of 4% (ranging from 1% to 8%) of live TAGB (Figure 2.6).

Differences in forest structure among forest types

Large tree density

The greatest differences in TAGB are attributable to the density of large trees. The average density for trees 70 - 200 cm dbh was greater in the dense and ecotone forests compared to the open forests (7 , 6 and 4 tree ha^{-1}, respectively,) while the heterogeneity of the forest types was reflected in the range of tree density between sites (1 - 6 tree ha^{-1}, open forests; 3 - 10 tree ha^{-1}, dense forests and 5 - 9 tree ha^{-1}, ecotone forests; Figure 2.4, Appendix A.1).

The largest trees ($\geq$200 cm dbh) were exceptional in the dense and ecotone forest averaging < 1 tree ha^{-1} but accounting for a mean for all sites of 16% and 14% of the aboveground biomass for all trees $\geq$ 10 cm dbh (Figure 2.4, Appendix A.1). The percentage of aboveground biomass for trees $\geq$ 10 cm dbh composed of the largest trees ranged from 22% to 42% in the dense forest and 18% to 32% in ecotone forests, for sites in which the size class occurred (Figure 2.4, Appendix A.1). The largest trees ($\geq$ 250 cm dbh) occurred in the two hill sites (24 and 25) in dense forests. The dense hill sites also had the highest average TAGB (488 Mg ha^{-1}). Compared to level sites on oxisols or latisols, the high biomass and very large trees found in the hill sites may be due to less weathered soils with a higher

nutrient content . Both hill sites had rock outcroppings not evident at other sites, indicating a shorter distance to active mineral weathering.

Trees < 70 cm dbh density

Though the average tree density for trees 10 - 50 cm dbh was similar for open, dense and ecotone forests the heterogeneity within forest types is evident in the range of tree density. The open and ecotone forests had the widest range, a difference of 240 and 262 trees ha^{-1} respectively between the highest and lowest values while, dense forests had the narrowest range , a difference of 150 trees ha^{-1}.

The heterogeneity of the forest is evident again in the 50 - 70 cm dbh class where average tree density was lower in the ecotone forests than in the open or dense forest (7 trees ha^{-1} in ecotone forests compared to 13 trees ha^{-1} in open and dense forests) (Figure 2.8, Appendix A.5). However, the range of tree density between sites was widest in the dense forest (3 to 28 trees ha^{-1}) while in the open and ecotone forest the range was about half that (8 to 18 trees ha^{-1} and 4 to 10 trees ha^{-1}, respectively; Figure 2.8, Appendix 2.5).

Vertical structure and density

We considered trees $\geq$ 70 cm dbh to be emergent from the canopy. These averaged 4 ha^{-1} (range l to 6 trees ha^{-1}) for open forests while in dense and ecotone forest they averaged 7 ha^{-1} (range 3 to 12 trees ha^{-1}, Figure 2.7, Appendix A.6). Trees 30 to 70 cm dbh form a high canopy with an average of 63 trees ha^{-1} (range 34 to 85 trees ha^{-1})in all 3 forest types. Trees 10 to 30 cm dbh form the mid

canopy with 350 trees ha^{-1} (range 175 to 464 trees ha^{-1}) for all three forest types. The understory was found to have a variable density of trees and palms < 10 cm dbh ranging from 2406 to 9796 individuals ha^{-1} (Figures 2.7 and 2.8, Appendix 2.5 and 2.6). In the herbaceous layer, basal leaf palms ranged from 0 to 1563 individuals ha^{-1} and seedlings < 1.37 m in height ranged from 109,000 to 307,000 individual ha^{-1}.

Comparative density

The mean density for trees ≥ 10 cm dbh was 419 trees ha^{-1} and ranged from 223 trees ha^{-1} in an ecotone site to 528 trees ha^{-1} in a dense site (Figure 2.4, Appendix 2.5). Klinge et al., (1975) reported 400 trees ha^{-1} for forests near Manaus, Amazonas, Brazil. Jordan and Uhl (1978) found 786 trees ≥ 10 cm dbh in a tierra firme forest of the Venezuelan Amazon. Brown,I.F., et al. (1995) found a density of 475 trees ha^{-1} (trees ≥ 10 cm dbh) for an open forest near Samuel Hydroelectric Reservoir in Rondonia, Brazil. One site (74), south of the Samuel Hydroelectric Reservoir , which was in the same forest type and area as the site reported by Brown, I.F., et al. (1995), had a similar density of 458 trees ha^{-1}.

Brown and Lugo (1992) using inventory data found trees > 70 cm dbh contributed no more than 3% (or 6 to 10 ha^{-1}) to the total number of trees ≥ 10 cm dbh. In our study we found that the trees ≥ 70 cm dbh contributed 3.8%, 7.1%, and 1.8% to the total number of trees ≥ 10 cm dbh in open, dense, and ecotone forests respectively and averaged 4 ha^{-1} (range 1 to 6 trees ha^{-1}) for open forests while in dense and ecotone forest they averaged 7 ha^{-1} (range 3 to 12 trees ha^{-1})

(Figure 2.7, Appendix 2.5). Part of the explanation for the differences between the estimate of Brown and Lugo (1992) and our field measurements may be due to the limited information on the number of smaller trees (< 30 cm dbh) available from inventory data. Brown and Lugo (1992) assumed that dense forests would have fewer trees ha^{-1} 10 - 30 cm dbh than open forests. Number of trees 10 - 30 cm dbh in open forests for our sites averaged 359 ha^{-1}, and in dense forests 379 ha^{-1}. In open forests trees 10 - 30 cm dbh contributed 84% of the total number of trees $\geq$ 10 cm dbh, and in dense forests they contributed 80%.

Basal area and QSD

Basal area for all trees combined was highest in the dense forests at 28 m^2 ha^{-1} (range 23 to 37 m^2 ha^{-1}, Figure 2.9, Appendix 2.7), while ecotone forest averaged 25 m^2 ha^{-1} (range 15 to 33 m^2 ha^{-1}), and open forests averaged 24 m^2 ha^{-1} (range 19 to 26 m^2 ha^{-1}). These values are consistent with those measured in other moist tropical forests. Basal area of dense forests in Rorima and Para, Brazil differed by 30 % (32 m^2 ha^{-1} and 24 m^2 ha^{-1} respectively, Higuchi et al., 1994). Lieberman and Lieberman (1987) found a basal area ranging from 27 to 31 m^2 ha^{-1} for stems $\geq$ 10 cm dbh at La Selva in Costa Rica, and Jordan and Uhl (1978) reported an average basal area of 33 m^2 ha^{-1} in tierra firme forests in Venezuela. In the tierra firme forest, basal area of the small size trees (< 10 cm dbh) was 11 m^2 ha^{-1}. Forest structure in our study gave a basal area of trees < 10 cm dbh ranged from 1 to 5 m^2 ha^{-1}. An open forest site at Samuel Hydroelectric reservoir in Rondonia had a basal area of 25 m^2 ha^{-1} for trees $\geq$ 10 cm dbh and a mean basal

area per tree of .052 m^2 (Brown et al., 1995). The basal area for trees $\geq$ 10 cm dbh for open forests for our study was 20 m^2 ha^{-1} with .047 m^2 per tree.

The QSD is used as a factor in some models to determine a volume expansion factor (VEF) to convert reported forest inventory values to biomass (Brown, 1997, Brown and Lugo, 1992, Gillespie et al., 1989). QSD is directly related to basal area (Table 2.2) and in our study ranged from 22 to 33 cm for trees $\geq$ 10 cm dbh both values occured in dense forest plots (Appendix A.8). QSD for trees $\geq$ 30 cm dbh ranged from 41 to 54 cm in open forests, 42 to 64 cm in dense forests and 47 to 62 cm in ecotone forests. In their biomass estimates Brown and Lugo (1992) assumed a QSD of > 35 cm for dense forests leading to a VEF of 1.25 and a smaller QSD of 25 cm for open forests, leading to a VEF of 1.5 . In our study we found the QSD's for open and dense forest types to be very similar (average for trees > 10 cm dbh was 25 cm in open forest and 27 cm for dense forests.

Conclusions

Our study provided a unique opportunity to compare the biomass of 20 tropical forest sites using a uniform method to quantify TAGB. The RADAMBRASIL sites provided a framework of forest classification for comparing the samples. The TAGB from the 20 sites indicated the variability within and among forest types in northern Rondônia, Brazil. Data collected on basal area, QSD, and non-tree components explained some of the difference between estimates derived from direct and indirect methods by quantifying components of TAGB not often measured.

The open and ecotone forests were more variable in the contribution to TAGB of both trees < 50 cm dbh and non-tree components within forest types than were dense forests. All three forest types from this study were highly variable in the contribution to TAGB of trees > 50 cm dbh. The narrower range of TAGB in open forests appears to be the result of the absence of trees > 200 cm dbh in the open forest. The average contribution of live non tree components to TAGB for all plots was 6.6%; for wood debris and standing dead, 8.9%; for litter/rootmat, 2.8%; for trees < 10 cm dbh, 3.6%; and trees > 10 cm dbh make up the remaining 79.1%. The results of this study decrease the uncertainty of biomass in the Amazonian rainforests, while pointing out that due to forest heterogeneity there are limits to the usefulness of forest delineations from RADAMBRASIL to predict biomass.

Chapter 3

Analysis of Projeto RADAMBRASIL as a Data Set Useful to Predict Total Aboveground Biomass of Forests in Rondônia, Brazil.

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Keywords: Tropical forest biomass, Biomass models, Brazil, Rondônia, Amazon forests.

Abstract

It is recognized that tropical forest ecosystems are significant global carbon pools and potential sources of atmospheric C, therefore accurate assessment of total aboveground biomass (TAGB) is necessary. It has been suggested that forest inventory data may be a good means of accurately calculating these pools. One such forest inventory is Projeto RADAMBRASIL. We tested the hypothesis that models based on the commercial volume reported in the RADAMBRASIL forest inventory could be used to estimate TAGB. In order to test the models we located 20 RADAMBRASIL forest inventory sites in Northern Rondônia and quantified the TAGB. TAGB for the resampled sites ranged from 288 to 345 Mg ha^{-1} (mean 313 Mg ha^{-1}); 298 to 534 Mg ha^{-1} (mean 377 Mg ha^{-1}); and 297 to 422 Mg ha^{-1} (350 Mg ha^{-1}) in open, dense and ecotone forest types respectively. The grand mean for all 20 sites was 341 Mg ha^{-1}. Area weighted mean (mean based on the total area represented by each forest type) was 334 Mg ha^{-1}. The results from this study were then compared to 2 models which use commercial tree volume (trees $\geq$ 30 cm dbh) from Projeto RADAMBRASIL to estimates TAGB. One model (Fearnside's model, 1992a) accounts for all biomass while the second model (Brown and Lugo's model, 1992) only estimates aboveground biomass of trees $\geq$ 10 cm dbh. The models were not good predictors of the forest biomass for specific sites or forest type means. The model for TAGB (Fearnside, 1992a) over-estimated the field measured TAGB from this study, while the model for TAGB of trees $\geq$ 10 cm dbh (Brown and Lugo, 1992) under-estimated TAGB. In open forests the Fearnside model over-estimated biomass by > 100 Mg ha^{-1} while in dense forests the Brown

and Lugo model under-estimated biomass by > 100 Mg ha^{-1}. Commercial tree volume and density reported in RADAMBRASIL for the sample sites had no relationship to TAGB, tree biomass, or density quantified in this study ($R^2 < 0.10$). Therefore, it was not possible to model TAGB from commercial volume reported in RADAMBRASIL. Results indicate that RADAMBRASIL data is not reliable to estimate TAGB. Estimates of C pools and loss from deforestation are dependent on the models used to derive TAGB and the use of forest classification as well as accurate determinations of the area deforested. This study identifies some of the error associated with modeled TAGB based on commercial volume reported in Projeto RADAMBRASIL.

Introduction

Tropical forests have been at the center of discussion about emissions of green house gases from land use change (Fearnside, 1992a, 1992b, 1993, 1997: Hall and Uhlig, 1991; Houghton, 1991a, 1995; Houghton et al., 1991). Some of the uncertainty in the carbon cycling and global climate change models stem from estimates of total aboveground biomass (TAGB) for tropical forest.

Estimates for TAGB in the Brazilian Amazon have ranged from 155 to 394 Mg ha^{-1} (Brown and Lugo, 1984, 1992; Brown et al.,1989; Fearnside, 1985, 1986, 1987, 1991, 1992a, 1992b; Kauffman et al.,1995). Differences in TAGB estimates arise, in part from the methods used to formulate the data base. The Fearnside (1985) and Kauffman (1995) estimates were based on field enumerated measurements whereas the Brown and Lugo (1992), and Fearnside (1992a, 1992b) estimates are based on an expansion factor for forest commercial volume reported in forest inventory data.

The costly nature and scarcity of destructive sampling or field enumerated biomass measurements makes commercial volume from forest inventories, with large data sets, desirable for calculating TAGB of Amazonian forests. Forest inventory data has an advantage in that there are many data points available but the disadvantage that the methods used are not specific to measure biomass and do not account for many of the components that make up TAGB such as litter, vines, palms, and small diameter trees (< 30 cm diameter at breast height (dbh)). Moreover, forest inventories generally have a focus on commercially valuable species of trees. Direct measurements or enumerated field biomass measurements

specifically for TAGB are scarce for the Amazon but include more (or all) elements of the TAGB.

A major program of Projeto RADAMBRASIL (DNPM, 1978) included a forest inventory of commercial volume with the objective of describing the potential economic value of forest resources of Brazil. RADAMBRASIL focused primarily on merchantable timber with a diameter at breast height (dbh) $\geq$ 30 cm. Most of the study plots were one hectare in size (10 x 1000 m). The data from RADAMBRASIL are reported in a 50 volume series covering the forested areas of Brazil (DNPM, 1978). Projeto RADAMBRASIL(Vol.16, Folha SC.20 Porto Velho, DNPM, 1978) identified a hierarchy of 57 forest types and sub types in the state of Rondônia, Brazil. Forest delineation varied from volume to volume. Based upon communication with scientists who interviewed RADAMBRASIL personnel, there are inconsistencies among sites and between volumes due to differences in the field crews and methods of analysis (Lucarelli, H, and Nepstad, D, personal communication; reported in Brown, I.F. et al., 1995, Fearnside, 1992a).

Information from the RADAMBRASIL inventory has been used in global models of carbon pools and flux (Dixon et al., 1994; Houghton et al., 1995; Fearnside, 1992a, 1993, 1997). However, due to the low estimates of biomass derived from models using the RADAMBRASIL data set compared to data collected in ecological studies, it's use is controversial (Brown and Lugo, 1992 and Fearnside, 1992a). Adding to the controversy, no study has examined the relationship between the data in the forest inventory and the quantification of TAGB by enumerated field measurements. This is necessary in order to ascertain if

forest inventory information can reliably predict TAGB and hence C pools. It was hypothesized that the more detailed information from our study could be scaled up to the larger data base of RADAMBRASIL increasing the accuracy of global carbon models essential to predicting climate change.

The objectives of this study were: (1) Determine if a quantifiable correlation exists between the TAGB estimates from this study and modeled estimates based on the RADAMBRASIL data set and (2) Develop a model based on the TAGB results from this study and the commercial volume reported in RADAMBRASIL.

Study Sites

Study sites were located in the northwestern portion of the state of Rondônia and the southern extreme of Amazonas state, Brazil (Chapter 2, Figure 2.1). Forests in this part of Amazonia are representative of forests within the "crescent" of deforestation occurring along the southern and eastern fringe of the Amazon (Skole et. al., 1994). Forests were classified by Projeto RADAMBRASIL as seasonal tropical evergreen forests transitional between evergreen tropical forests and semi deciduous tropical forests (DNPM, Brazil, 1978). Under the Holdridge system, they would be classified as tropical moist forests (Holdridge, 1971). Based on climatological data from Porto Velho (the closest station to the sites) the average annual rainfall is ≈ 2300 mm with the majority falling between November and April (DNPM, Brazil, 1978). Mean temperature is 25.2° C (average maximum of 31.1° C, and average minimum of 20.9° C), and average relative humidity is 85% (Departimento Nacional de Meterologia, Brasil, 1992). Soils at the individual sites

range from upland red-yellow and yellow oxisols, red-yellow ultisols, to alluvial soils with hydromorphic lateritic, and gley characteristics (DNPM, BRAZIL, 1978). The elevation at the sites ranged from 61 to 310 m:

We sampled 20 sites across 9 forest classifications from Projeto RADAMBRASIL (Vol.16; Folia SC. 20 Porto Velho; Geologia, Geomorfologia, Pedologia, Vegetaçao e Uso Potencial da Terra (RADAMBRASIL); DNPM, Brazil, 1978) (Chapter 2, Table 2.1). Each of the 20 sites were forest inventory sites sampled as part of RADAMBRASIL in the early 1970's. Study plots were labeled using the original numbers of the forest inventory plots of the RADAMBRASIL study. The RADAMBRASIL classification system was based on a hierarchy of ecological regions (i.e., forest types), subregions (i.e., ecological/geomorphology sub-groupings) and formations (i.e., topographic differences). The most coarse resolution classifies our study sites into 3 forest types: (1) "open" (characterized by well spaced individual trees, numerous palms and the presence of vines); (2) "dense" (normally having 3 strata; one of large trees, one of small regenerating trees and one of shrubs and herbaceous material); and (3) "ecotone" (edge forests in contact with savanna and different classes of forest formations) tropical forest. A fourth forest type (represented by 1 plot) classified as anthropogenic disturbance also was identified as open forest. Open forests are the most abundant forest type in Rondônia (DNPM, Brazil, 1978). The 8 subregions (based on the geomorphology of the area) represented in this study ranged from open, Amazonian alluvial terraces to dense southern Amazonian submontane low hills (Chapter 2, Table 2.1).

Many of the plots had minor levels of human impact. However the level of disturbance in sample plots did not appear to be greater than that reported at the time of the RADAMBRASIL inventory. For example, subsistence palm and tree harvest for local use and trails used for rubber tapping were reported in the original inventory. Some sites (i.e.;1 ,2, 225, 226 and 218) were located near areas of long term (>100 yrs.), low density (euro American) settlement and therefore we can assume that there has been ongoing low level impacts on forest structure and composition. Five of the 20 sites had at least 1 stump indicating past selective tree harvest; site 75 and 229 each contained 3 stumps, site 76 had 2, site 25 had 1, and site 113 had 6 stumps. All the stumps originated > 20 years prior to our study.

Methods

Plot site selection

There were a total of 229 forest inventory sites in Volume 16, Porto Velho, which covered the area of northern Rondônia and Southern Amazonas for Projeto RADAMBRASIL (DNPM, 1978), but we limited ourselves to the northern part of the region due to logistics. Selection of RADAMBRASIL plots for resampling in this study was based on continued existence of the forested plot site (many sites had been deforested) and accessibility. Plots were accessible by a combination of automobile, boat, and hiking. The aforementioned criteria eliminated all but 59 possible sites. The 20 plots selected to be used in this study were assumed to be representative of undisturbed Rondônian forests; there was no a priori knowledge

of either biomass or structure (other than the RADAMBRASIL classification) of these study sites. Geographical locations of the sites were determined from maps and coordinates provided by D. Skole, University of New Hampshire, and located in the field using a Global Positioning System (GPS) (Chapter 2, Table 2.1). We also used a RADAMBRASIL map and satellite photos of the area to assist in plot location. In cases where the area containing the original RADAMBRASIL sites had likely been deforested (i.e. adjacent to a road), we moved our plots to the closest intact forest still within the same forest type, usually a short distance (≈ 200 m) from the road. Our assumption was that if the data from the inventory RADAMBRASIL are relevant to estimate TAGB, then the slight differences in relocation should not be an important influence on results.

Total aboveground biomass components

TAGB was estimated by measuring all organic materials above mineral soil. Partitioning of TAGB was based on structural and ecologically significant components and practicality of measurement (Chapter 2, Figure 2.2). Trees were separated into 6 diameter classes based on dbh (0-10, 10-30 ,30-50, 50-70, 70-100, 100-200 and 200-300 cm dbh). Tree diameter was measured at 1.37 m above the ground (dbh) or immediately above the tree buttress or stilt roots when present. Palms were divided into three categories (basal palms with no trunks, <10 cm dbh, and ≥ 10 cm dbh) and vines or lianas into two size classes (<10 cm dbh and ≥ 10 cm dbh). Other components included small dicots (plants <1.37 m in height), litter/rootmat (forest floor), standing dead trees and palms, and dead and

downed coarse wood debris (CWD), the latter divided into two categories 2.5 - 7.5 cm diameter and $\geq$7.5 cm diameter (diameter of CWD measured at the point of intersection with the transects).

Plot layout

At each site a 75 m x 105 m (0.79 ha) plot was established (Chapter 2, Figure 2.3). Two 105 m transects divided the plot into 3 - 25 m x 105 m (0.26 ha) subplots. The diameter for all trees $\geq$ 30 cm dbh was recorded in the entire plot (0.79 ha). All trees and palms 10 - 30 cm dbh were measured in the center subplot. Along each 105 m transect, we established a planer intersect transect to measure coarse wood debris (CWD) every 15 m (n = 16; 8/transect) (Brown and Rossopoulous 1974; Van Wagoner 1968). At each of the 15 m points along the transect, a 2 x 10 m belt transect was established to measure small trees, vines and palms (> 1.37 m in height, but < 10 cm dbh) and basal leaf palms. At the same 15 m points along the 105 m transect, the biomass of the forest floor was measured in a 50 x 50 cm microplot and density of dicot seedlings in a 1 x 1 m plot was measured.

Procedures

Equations used for calculating each component of the biomass are listed in Chapter 2, Table 2.2 and 2.3.. Diameter of trees was measured with a forestry caliper or dbh tape. Biomass of trees < 5 cm dbh was calculated from equations based on dbh given by Hughes (1997). The biomass of trees $\geq$ 5 cm dbh were

calculated from equations based on dbh given by Higuchi (1997) for Amazonian trees, or the general moist tropical forests equations from Brown et al. (1989). The two different individual tree models were used to test the difference in biomass that resulted from the use of each model on the same tree data.

Biomass of CWD was calculated using the methods of Van Wagner (1964). Transects to measure mass of CWD > 7.5 cm diameter were 15 m in length. CWD 2.5 - 7.5 cm in diameter were measured along 5 m of the 15 m transect. The CWD was further separated into tree (dicot) wood or palm wood components. The $\geq$7.5 cm diameter class was also separated into sound or rotten classes. One hundred samples for each diameter class were collected in forests near Jamari, Rondonia, to obtain an average wood density. For the 2.5-7.5 cm diameter classes the diameter and angle of 65 individuals along a 100 m transect were measured to calculate the quadratic mean diameter and fuel particle tilt, and to correct for wood particle tilt (Brown and Roussopoulous, 1974). Thereafter, we only counted pieces that intersected the line and used the quadratic mean diameter to calculate biomass.

To calculate forest floor biomass, each sample was initially weighed in the field. Sub-samples were then oven dried to determine the ratio of wet to dry weight. This ratio was then applied to the entire sample to convert from wet to dry weight.

The number of leaves on each basal leaf palm encountered in the 2 x 10 m plot was counted and multiplied by a mean weight per leaf derived from a random sample of 30 basal leaves that were oven dried and weighed. Three equations are necessary to ascertain biomass of palms; biomass of *Attlea* sp. $\geq$ 1.78 m high was

calculated using the model by Anderson (1983), that of other palm species $\geq$ 10 cm dbh estimated using the model of Frangi and Lugo (1985), and that of palms < 10 cm dbh calculated using the model of Hughes (1997).

Seedling biomass (< 1.37 m ht.) was based on sub-sample of 50 oven dried plants from which an average weight per seedling was determined, the number of seedlings were then multiplied by the average to determine biomass. Vine biomass estimates were calculated by the model given by Putz et al., (1983).

Standing dead tree aboveground biomass < 10 cm dbh, were calculated from an equation developed by Hughes (1997), while for standing dead trees $\geq$ 10 cm dbh volumes were first calculated then multiplied by the mean value of specific gravity of dead wood (0.413 g/cm^3, the value for sound CWD). Standing dead palm biomass was estimated from Hughes (1997) for palm < 10 cm dbh or from volume multiplied by specific gravity (0.327 g/cm^3) for palms $\geq$ 10 cm dbh.

Comparison of modeled TAGB based on RADAMBRASIL and TAGB calculated in this field study.

Individual tree biomass from our field data were calculated first with the model for moist tropical forest presented by Brown et al. (1989) and then with an Amazon forest specific model suggested by Higuchi (personal communication, 1997). The Brown individual tree model was derived from data collected on 168 trees ranging from 5 to 130 cm dbh in moist tropical forest globally. The Higuchi individual tree model was based on 307 tees ranging from 5 cm dbh to 120 cm

dbh in the Brazilian Amazon. The TAGB estimates resulting from the two individual tree models were compared using a paired t-test.

TAGB for the RADAMBRASIL sites of our study were also estimated from expansion factors and models developed by Fearnside (1992) and Brown and Lugo (1992). Those are referred to as the "Fearnside" and "Brown / Lugo" models in this study. Biomass calculation of trees $\geq$ 10 cm dbh with the Brown / Lugo model involves first expanding the commercial volume for trees $\geq$ 30 cm dbh from RADAMBRASIL to the volume at 10 cm dbh. Then converting the volume, by multiplying it by average wood density (specific gravity), to stemwood biomass, and expanding the stemwood biomass to total aboveground biomass (TAGB). The equation was:

*TAGB (trees $\geq$ 10 cm dbh) = VEF * WD * BEF*

Volume expansion factor (VEF) = 1.25 for dense forests and 1.50 for open forests

Wood density (WD) = 0.69 Mg/m^3

Biomass expansion factor (BEF) = $\exp\{3.213 - 0.506 * \ln(SB)\}$ for SB < 190 $Mg\ ha^{-1}$

or 1.74 for SB $\geq$ 190 $Mg\ ha^{-1}$

*Stemwood biomass (SB) = Commercial volume (RADAMBRASIL) * VEF * WD*

The Fearnside model uses adjustments to the Brown / Lugo model to account for factors affecting aboveground biomass (Table 3.1). In our calculations using the Fearnside model we omitted factors for belowground biomass, as it was not measured in our field study.

Table 3.1. Adjustments to TAGB from the Brown / Lugo model used by Fearnside (1992a).

Factor	Correction multiplier	Percent adjust-ment
Adjustment to aboveground live biomass:		
Hollow trees	0.9077	-9.23
Vines	1.0425	4.25
Other non tree components	1.0021	0.21
Palms	1.0350	3.50
Trees < 10 cm dbh	1.1200	12.00
Trees 30 - 31.8 cm dbh	1.0360	3.60
Bark (volume and density)	0.9856	-1.44
Sapwood (volume and density)	0.9938	-0.62
Form factor	1.1560	15.60
Net adjustment to live aboveground:	1.2787	27.87
Adjust ment for other components (with respect to values for aboveground live biomass after correction):		
Dead aboveground biomass:	1.0903	9.03
Bellow ground	1.3428	34.28
Net adjustment for other components:	1.4331	43.31
Total adjust ment:	1.8325	83.25

The Brown / Lugo and Fearnside model estimates were tested against the results of the field data estimates (based on the means at the forest type - regions, geomorphic - subregion, topographic - formation and individual plot levels of vegetation organization) by a paired t-test. We used regression analysis to determine if there was a relationship between our field measured biomass estimates and those modeled from commercial volume in the RADAMBRASIL forest inventory.

Comparison of TAGB area weighted means from the Fearnside model, Brown / Lugo model and TAGB estimates from this study

Commercial volumes reported in RADAMBRASIL were compiled into statistical analysis based on the forest classification level of geomorphic subregion this is comparable to TAGB from our study at the same level (Projeto RADAMBRASIL Vol. 16. Folha SC 20 Porto Velho IV-Vegetacao, Analise Estatistica de dados. DNPM, 1978) . Land area delineated in each geomorphic subregion that comprises the total area surveyed by Projeto RADAMBRASIL in Folha SC 20 Porto Velho (DNPM, 1978) extending from longitude 66^0 to 60^0 and latitude 8^0 to 12^0 totals 262,110 km^2 (Table 3.2). The sites sampled in this study represent 8 of the 12 geomorphic subregions identified by RADAMBRASIL (Table 3.3). The most resampled sites (6) for an individual geomorphic region were located in the open tropical forest type, in the broken surface of the upper Xingu/Tapajos/Madiera river formations. These 6 sites represent 48% of the land area. The areas of ecological tension, savanna/forest edge subregion represent 14% of the land area and 4 of the resampled sites are located in that vegetation type. Representative sites were resampled for geomorphic subregions covering 80% of the land area. At the forest type - regional level all 4 of the regions have representative sites (8, 7, 4 and 1 sites for open, dense, ecotone and human influenced respectively).

Forest biomass at state-wide scale was estimated using mean TAGB for forest types and geomorphic subregions from each method of estimation (Brown / Lugo, Fearnside and this study). The area of land covered by the subregion multiplied by the mean TAGB for that subregion gave an area weighted biomass for the forest

type and/or subregion. The sum of the weighted biomass for each subregion gives an area weighted biomass for the state of Rondônia. The weighted biomass of Rondônia divided by the total area yields an area weighted mean biomass (Mg ha^{-1}) for the forests in Rondônia and the southern edge of Amazonas covered in RADAMBRASIL vol.16 (DNPM, 1978). TAGB for the same area based on the mean for the coarser level of classification by forest type (open, dense, ecotone and areas of human influence) was calculated in the same way, thus giving a weighted mean (Mg ha^{-1}) based on the total forest area classified into type.

Correlation of RADAMBRASIL tree density and commercial volume to TAGB and tree density derived from this study.

To test the replicability of the RADAMBRASIL study, the density of trees > 30 cm dbh quantified in our study compared to density of trees >30 cm dbh reported in RADAMBRASIL by a paired t-test, to determine if the sample was unusual. Linear regression was used to asses the relationship of our density and aboveground biomass of trees $\geq$ 30 cm dbh by geomorphic subregion mean and individual site to the RADAMBRASIL reported tree density and commercial volume respectively. In the same manner TAGB from the means by geographic subregions and individual sites from our data were regressed on the RADAMBRASIL commercial volumes to determine the feasibility of creating a model for TAGB based on commercial volume. The data were analyzed with a log transformation were necessary to improve the fit.

Table 3.2. Forested land area (km^2) of Rondonia, Brazil (60° - 66° Longitude and 8° - 12° Latitude) by region and sub-region as delineated in RADAMBRASIL Vol. 16 Porto Velho Vegetaçao (DNPM, 1978: pg 101).

Forest type - Region	Geomorphic - Subregion	Area (Km^2)	Percent of total area
Open tropical forest	Amazonia alluvial	1,472.03	0.6
	Flat surface of accumulation	12,024.32	4.6
	Low plates of Amazonia	12,475.56	4.8
	Broken surface of the upper Xingu/Tapajos/Madeira	126,492.56	48.2
	Pre - Cambrian platform cover	12,010.38	4.6
Dense tropical forest	Amazonia alluvial	2,887.68	1.1
	Low plates of Amazonia	12,616.68	4.8
	Broken surface of the upper Xingu/Tapajos/Madeira	11,940.05	4.5
	Low hills of the southern Amazonia mountains	15,688.77	6.0
	Pre - Cambrian platform cover	2,790.77	1.1
Areas of ecological tension	Savanna / Forest edge	36,482.38	13.9
Others		3,073.25	1.2
		12,155.57	4.6
TOTAL		262,110.00	100.0

Table 3.3. The mean and range (Mg ha^{-1}) of total above ground biomass (TAGB). RADAMBRASIL sites grouped by region and subregion. Groupings were from RADAMBRASIL Vol. 16 Porto Velho Vegetaçao (DNPM, 1978

Forest type - Region	Geomorphic - Subregion	Mean ± SE This study	Range, This Study	Number of sites
Open tropical forest	Amazonia alluvial	308.50 ± 20.27	288.22 - 328.77	2
	Flat surface of accumulation	-	-	-
	Low plates of Amazonia	-	-	-
	Broken surface of the upper Xingu/Tapajos/Madeira	313.82 ± 7.42	294.65 -345.67	6
	Pre - Cambrian platform cover	-	-	-
Dense tropical forest	Amazonia alluvial	363.40 ± 44.27	319.13 - 407.67	2
	Low plates of Amazonia	299.52	299.52	1
	Broken surface of the upper Xingu/Tapajos/Madeira	-	-	-
	Low hills of southern Amazonia	487.76 ± 46.08	441.68 - 533.83	2
	Pre - Cambrian platform cover	317.27 ± 19.15	298.11 - 336.42	2
Areas of ecological tension	Savanna / Forest edge	350.23 ± 26.18	297.91 - 422.14	4
Human influence		287.34	287.34	1

- indicates no data for this geomorphic subregion.

Results

<u>Comparison of modeled TAGB based on RADAMBRASIL and TAGB calculated in this field study.</u>

The Higuchi individual tree biomass model was used to calculate tree biomass in this study. There was no significant difference ($p = 0.41$) between mean TAGB using the model for individual tree biomass presented by Brown, et. al, (1989) for tropical moist forests and that of Higuchi (personal communication 1997). For example the TAGB of all sites was calculated to be 341 Mg ha^{-1} using the Higuchi individual tree model and 344 Mg ha-1 using Brown, et. al,(1989) individual tree model (TABLE 3.4). The Higuchi individual tree model was based on a destructive sample of trees in the Amazon Basin and therefore may be more appropriate for trees in the region of this study.

TAGB estimates from the Brown / Lugo model and Fearnside model were tested against the TAGB estimates from our study at the geomorphic and topographic mean levels of community type partitioning. The tests at those levels were inconclusive due to the small irregular sample sizes. A t-test of means at the level of forest type yielded no differences in TAGB for open forest between the Brown / Lugo model and estimates from this study ($p = 0.74$) but differences from the Fearnside model (mean 35% higher) estimate ($p = 0.01$). Open forest TAGB estimates from our study, Brown / Lugo and Fearnside models were 313, 306 and 408 Mg ha^{-1}, respectively (Table 3.4). In the dense forest type there was a difference between the Brown / Lugo model and our TAGB estimates (mean 28%

Table 3.4. Comparison of total above ground biomass (TAGB, Mg ha⁻¹) for RADAMBRASIL sites using 4 models for calculations. Models based on forest inventory data (Brown and Lugo, 1992; Fearnside, 1992a) and TAGB from data from this study and models for individual tree biomass (Brown, 1989 and Higuchi, 1997, unpublished data).

Forest type -Region	Geomorphic - Subregion	Site	RADAMBRASIL inventory: Brown and Lugo 1992 (Trees > 10)	RADAMBRASIL inventory: Fearnside 1992a	Individual tree data: Brown et.al., 1989	Individual tree data: Higuchi, 1997
Open tropical forest	Amazonia alluvial	225	316.10	440.69	326.79	328.77
		226	377.36	526.10	276.75	288.22
		Mean	346.73 ± 30.63	483.39 ± 42.73	301.77 ± 25.02	308.50 ± 20.27
	Broken surface of the upper Xingu/Tapajos/Madeira	70	335.06	462.13	345.26	345.67
		74	254.80	355.23	293.40	295.65
		75	307.76	429.07	311.49	311.50
		76	335.29	467.45	315.94	310.84
		Topo Mean	308.23 ± 18.95	433.79 ± 28.56	316.52 ± 10.75	315.66 ± 10.73
		89	302.62	421.90	296.54	299.41
		113	218.91	305.20	318.10	320.86
		Topo Mean	260.77 ± 41.86	363.55 ± 58.35	307.32 ± 10.78	310.14 ± 10.72
		S.Reg Mean	292.41 ± 18.99	407.65 ± 27.79	313.45 ± 7.60	313.99 ± 7.42
	Mean Open forests		305.99 ± 17.48	425.97 ± 24.23	310.53 ± 7.55	312.75 ± 6.66
Dense tropical forest	Amazonia alluvial	1	250.98	349.91	433.09	407.67
		2	221.79	309.21	320.30	319.13
		Mean	236.38 ± 14.60	329.56 ± 20.35	376.69 ± 56.39	363.40 ± 44.27
	Low plates of Amazonia	229	323.45	450.94	288.46	299.52
	Low hills of southern Amazonia	24	259.57	361.88	563.63	533.83
		25	254.28	354.51	464.74	441.68
		Mean	256.92 ± 2.64	358.20 ± 3.69	514.18 ± 49.45	487.76 ± 46.08
	Pre - Cambrian platform cover	43	432.31	602.71	293.21	298.11
		44	159.16	221.89	324.63	336.42
		Mean	295.73 ± 136.58	412.30 ± 190.41	308.92 ± 15.71	317.27 ± 19.15
	Mean Dense forests		271.65 ± 32.55	378.72 ± 45.39	384.01 ± 39.69	376.62 ± 33.43
Areas of ecological tension	Savanna / Forest edge	186	287.28	400.52	365.42	348.34
		188	195.08	271.97	300.85	297.91
		190	296.51	413.38	435.97	422.14
		195	260.63	363.36	330.60	332.55
	Mean Ecotone forests		259.87 ± 22.90	362.31 ± 31.93	358.21 ± 29.08	350.23 ± 26.18
Human Influence		218	167.32	233.27	286.74	287.34
Grand Mean			277.81 ± 15.22	388.13 ± 21.40	344.60 ± 22.73	341.23 ± 14.17

less) but no difference between the Fearnside model and our TAGB estimates ($p = 0.09$ and $p = 0.64$, respectively). Dense forests TAGB from our study, Brown / Lugo and Fearnside models were 377, 272, and 378 Mg ha $^{-1}$, respectively. The ecotone forest type revealed a difference between the Brown / Lugo model and our TAGB estimate (mean26% less) ($p < 0.00$) and no difference between our TAGB estimates and Fearnside's estimates ($p = 0.16$). Ecotone forest TAGB from our estimates, Brown / Lugo and Fearnside models were 350, 259, and 362 Mg ha $^{-1}$, respectively. Comparing the grand means resulting from the Brown / Lugo model, Fearnside model and our TAGB estimates shows a difference between the Brown / Lugo model and our estimates ($p =$ 0.00, t-test) as well as the Fearnside model and our estimates ($p = 0.08$). The Brown / Lugo model grand mean estimate averaged 18% lower and Fearnside model grand mean estimate 14% higher than our estimate.

If forest inventories are useful to estimate TAGB, there should be a strong correlation between modeled TAGB based on inventories and TAGB from our field measured estimates. Both the Brown / Lugo and Fearnside models are based on the RADAMBRASIL forest inventory commercial volume and expansion factors or ratios (as described in the introduction and methods) consequently, they have the same basis at each site and are parallel in relationship to the RADAMBRASIL commercial volume values. However there was no correlation between either the Brown / Lugo or Fearnside models and the field quantified estimates of TAGB at the level of either individual plot or topographic formation ($R^2 = < 0.05$) (Table 3.5).

Table 3.5. Results of linear regression relating our estimates of total aboveground biomass (TAGB) to modeled estimates based on commercial volume in the RADAMBRASIL forest inventory.

TAGB field estimate (*TAGB for trees > 10 cm dbh) vs:		R^2 value	p - value
Individual sites (n = 20)	Brown/Lugo model TAGB	0.0073	0.72
	Brown/Lugo model TAGB *	0.0031	0.82
	Fearnside model TAGB	0.0152	0.60
Means from geomorphic and topographic types (n = 9)	Brown/Lugo model TAGB	0.0076	0.82
	Brown/Lugo model TAGB*	0.0418	0.60
	Fearnside model TAGB	0.0147	0.76

For example in dense forest, low hills of S. Amazonia site the Fearnside model predicted mean TAGB was 358 Mg ha^{-1} and the Brown / Lugo model predicted 257 Mg ha^{-1} while our estimate was 488 Mg ha^{-1} (sites 24 and 25). In open, broken surface of the upper Xingu/Tapajos/Madiera, submontain hills Brown / Lugo and Fearnside models estimated mean TAGB to be 308 and 434 Mg ha^{-1} respectively, while our field quantified estimate was 316 Mg ha^{-1}. Log transformations did not improve the fit of the regressions.

Comparison of TAGB area weighted means from the Fearnside model, Brown / Lugo model and TAGB estimates from this study

Estimated weighted mean TAGB for the 80% of the land area represented by resampled sites shows the magnitude of differences among the models (Table 3.6). The weighted mean from our estimate was 331.5 Mg ha-1, for the Bown / Lugo

Table 3.6. Regional total above ground biomass (TAGB) pools and weighted means based on estimates from 2 commercial volume models and estimates from this study. Means are in units of Mg ha^{-1} . TAGB of areas are in Pg. Resampled Regions represent 80.3% of the total area.

Forest type - Region	Geomorphic - Subregion	Mean (mg ha^{-1})	RADAMBRASIL based models:		% of total area	TAGB of regions and subregions (Pg ha^{-1})		
		this study	Brown	Fearnside		This study	Brown	Fearnside
Open tropical forest	Amazon alluvial	308.5	346.7	483.4	0.6	0.0454	0.0510	0.0712
	Flat surface of accumulation	-			4.6			
	Low plates of Amazon	-			4.8			
	Broken surface of the upper X/T/M	313.8	292.4	410.4	48.2	3.9717	3.6988	5.1571
	Pre - Cambrian platform cover	-			4.6			
	Mean for Open forests	312.8	306.0	426.6	62.8	5.1440	5.0328	7.0163
	Weighted mean for open forests	313.9	293.0	408.52				
Dense tropical forest	Amazon alluvial	363.4	236.4	329.6	1.1	0.1049	0.0683	0.0952
	Low plates of Amazon	299.5	323.5	450.9	4.8	0.3779	0.4081	0.5689
	Broken surface of the upper X/T/M	-			4.5			
	Low hills of southern Amazon	487.8	256.9	358.2	6.0	0.7652	0.4031	0.5620
	Pre - Cambrian platform cover	317.3	295.7	412.3	1.1	0.0885	0.0825	0.1151
	Mean for Dense forests	376.6	271.7	378.7	17.5	1.7296	1.2475	1.7392
	Weighted mean for dense forests	393.3	283.1	394.6				
Areas of ecological tension	Savanna / Forest edge	350.2	259.8	362.3	13.9	1.2778	0.9481	1.3217
Others		-			1.2			
		287.3	167.3	233.3	4.6	0.3493	0.2034	0.2836
TAGB for area represented by re-sampled sites (80.3%) using subregional means.						6.9808	5.8632	8.1741
TAGB for total area (100%) using forest type means (open, dense and ecotone forests)						8.5889	7.4832	10.4326
TAGB (Mg/ha) weighted for 80% area represented by each subregion.		333.9	278.4	388.2				
TAGB (Mg/ha) weighted for 100% area represented by each forest type.		327.7	285.5	398.0				

model it was 278.4 Mg ha^{-1}, and for the Fearnside model it was 388.2 Mg ha^{-1}. The total regional biomass (80 % of the area) was about 1 Pg difference between each of the three estimates. The Brown estimate was the lowest (5.86 Pg) followed by the our field estimate (6.98 Pg) and the Fearnside estimate (8.17 Pg; Table 3.6).

If the means by the forest type are used in the calculation of the weighted biomass we can assume that the mean extends to include all the subregions and yields a total weighted biomass for 100% of the area. The weighted mean calculated from the mean by forest type yield slightly different results than that weighted by subregion. The weighted mean for our estimate was reduced by ≈ 4 Mg ha^{-1}, the Brown / Lugo estimate increased ≈ 1 Mg ha^{-1} and the Fearnside estimate increased by ≈ 10 Mg ha^{-1}. Calculating the biomass for 100% of the area using the forest type mean resulted in a difference of ≈ 1 Pg between our estimate (8.59 Pg) and the Brown estimate (7.48 Pg) , but a ≈ 1.5 Pg difference between our estimate and the Fearnside estimate (10.43 Pg; Table 3.6).

<u>Correlation of RADAMBRASIL tree density and commercial volume to TAGB and tree density derived from this study.</u>

There was no difference between the mean tree density (trees > 30 cm dbh) from RADAMBRASIL data and that enumerated in this study (paired t-test, $p = 0.37$). According to data reported in RADAMBRASIL the individual sites chosen for resampling in this study were similar in commercial volume and density of trees > 30 cm dbh to the mean for other RADAMBRASIL sites in the each subregion (DNPM, 1978; Table 3.7).

Table 3.7. Summary of means for subregions and individual resampled sites commercial volume (m^3 ha^{-1}) and tree density for trees $\geq$30 cm dbh (Trees ha^{-1}) reported in RADAMBRASIL Vol. 16 Porto Velho Vegetaçao (DNPM, 1978) and tree density from this study.

Forest type - Region	Geomorphic - Subregion	Plot	Page No.	Trees $\geq$30 cm dbh (numbers ha^{-1})			Commercial volume with bark (m^3 ha^{-1})	
				This study	RADAM inventory	No. of Species	All sites in the subregion	Resampled sites.
Open tropical forest	Amazonia alluvial	225 226	467	70 83	81 87	31 50		**166.25** **209.54**
	Mean for this subregion			77±7	84±3		**187.90±27**	**187.89±22**
	Broken surface of the upper Xingu/Tapajos/Madeira	70 74 75 76	436	69 58 67 61	93 48 68 64	53 27 41 37		**186.05** **107.46** **157.49** **186.18**
		89 113		62 84	82 45	47 29		**152.21** **79.03**
	Mean for this subregion			67±4	54±2	33	**144.84±18**	**114.82±16**
Dense tropical forest	Amazonia alluvial	1 2	138	46 93	51 58	30 35		**125.07** **97.38**
	Mean for this subregion			69±23	61±13	34	**135.91±30**	**111.22±14**
	Low plates of Amazonia	229	494	63	82	44		**209.34**
	Mean for this subregion				66±16		**154.09±55**	
	Low hills of southern Amazonia	24 25	220	91 64	75 63	41 34		**133.88** **128.41**
	Mean for this subregion			77±14	63±5	37	**127.37±15**	**131.15±3**
	Pre - Cambrian platform cover	43 44	333	75 69	88 29	40 22		**288.07** **49.74**
	Mean for this subregion			72±3	52±19	30	**129.36±76**	**168.90±119**
Areas of ecological tension	Savanna / Forest edge	186 188 190 195	695	50 48 74 76	67 48 64 55	48 25 38 40		**137.00** **62.58** **146.05** **112.49**
	Mean for this subregion			62±8	57±5	32	**99.42±13**	**114.23±19**
Human Influence		218	801	65	30	18		**45.87**
	Mean for this subregion				43±8	26	**79.20±17**	

There was no correlation between the tree density quantified in this study and that reported by RADAMBRASIL (R^2 = 0.095 p=0.42). Similarly, no relationship existed between the aboveground biomass of trees $\geq$30 cm dbh from this study and the commercial volume reported in RADAMBRASIL (R^2 = 0.107, p=0.39) or TAGB from this study and RADAMBRASIL commercial volume (R^2=0.008, p = 0.82). Log transformations did not improve the relationship.

Discussion

Comparison of modeled TAGB based on RADAMBRASIL and TAGB calculated in this field study

This field experiment was the first comparison of independently collected field data to test RADAMBRASIL commercial volume based models. The lack of a relationship between our estimates of TAGB and the estimates using the Brown / Lugo and Fearnside models indicates that the RADAMBRASIL data set can not be used to predict TAGB. There are several possible factors to explain the differences in the TAGB estimates from models using commercial volume compared to our enumerated TAGB. Among those factors are the inconsistencies between inventories designed to assess commercial value put into use to determine biomass, variation in the contribution of biomass components other than trees, and errors in the terms used in the models. The factors that can be addressed by this study are, the contribution of the non-tree components, contribution of the trees to the biomass, and how the tree and non tree components relate to terms used in the Brown / Lugo and Fearnside models.

To determine the TAGB, the Brown / Lugo model used expansion factors and wood density of the commercial volume of trees $\geq$ 30 cm dbh to extrapolate the biomass of trees 10 to 30 cm dbh (Brown and Lugo, 1992). Quadratic stand diameter (QSD, i.e., diameter of a tree with mean basal area; Husch et al., 1972) is one of the variables for determining the volume expansion factor (VEF) used (Brown and Lugo, 1992; Brown et al., 1989). The VEF is related to the size of trees that make up the forest with higher expansion factors in forests with smaller trees (low QSD) (Brown et al., 1989). In applying the Brown / Lugo model to the RADAMBRASIL data set, it was assumed that the open forest type would have a lower QSD ($\approx$ 25 cm) than the dense forest type (> 30 cm). Therefore a VEF of 1.25 was used for forests classified as dense while a VEF of 1.5 was applied to open forests (Brown and Lugo, 1992). In our study we found the QSD was approximately equal among the forest types (Chapter 2, Appendix A.8). The calculated mean QSD for trees $\geq$10 cm dbh was 24.8$\pm$2.7, 26.6$\pm$1.5, and 27.2$\pm$5.9 for open, dense, and ecotone forest types respectively. Calculating the mean QSD for trees $\geq$30 cm dbh (comparable to the RADAMBRASIL inventory) values where 48.0$\pm$1.3, 54.4$\pm$4.6, and 54.6$\pm$3.4 for open , dense, and ecotone forest types respectively. The difference in the VEF used in Brown / Lugos model could account for the result of open forest with higher biomass than that of closed forests. This was quite the opposite of the field measurements (Figure 3.1). Given that the Brown / Lugo model grossly underestimates dense forest, a higher VEF would improve this model (Figure 3.1). Due to the Fearnside models reliance on the Brown / Lugo model results, the error is carried over from one estimate to the

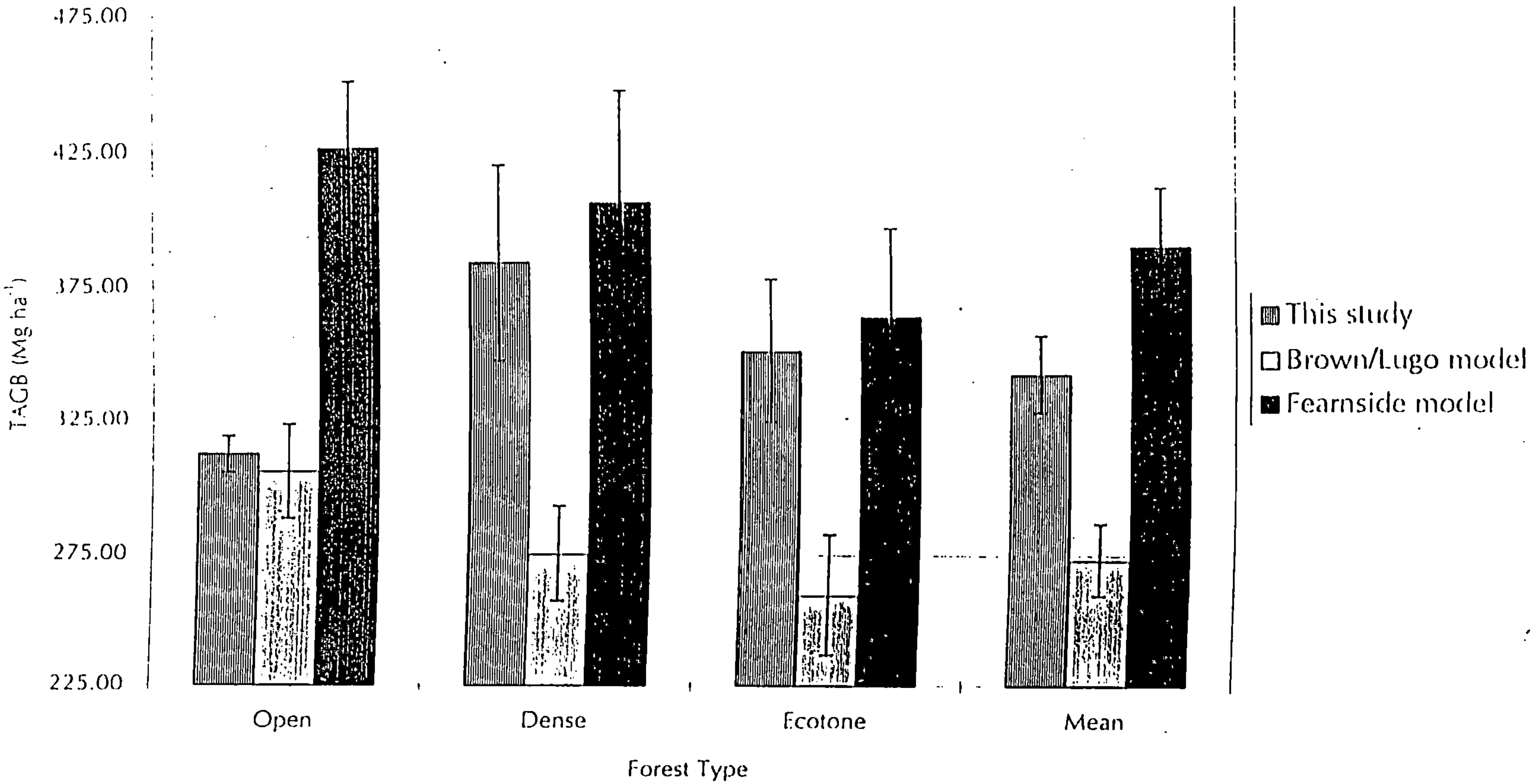

Figure 3.1. Comparison of total above ground biomass (TAGB) estimates from this study to 2 model estimates based on commercial volume from RADAMBRASIL forest inventory.

other. The results from the Fearnside model substantially overestimate the open forest TAGB but is reasonably close in estimating the dense forest TAGB through a combination of errors.

There are several assumptions made on the contribution to TAGB of vegetative components other than trees. The Brown / Lugo model did not include the contribution of components other than trees $\geq$ 10 cm dbh to TAGB. To correct for that omission, Fearnside (1992b) used a correction multiplier based on direct measures from the literature (Revilla Cardenas, 1986, 1987, 1988; Klinge et al., 1975; Jordan and Uhl, 1978; N. Higuchi, reported in Fearnside, 1992b; D. A. Da Silva reported in Fearnside, 1992b) on the values derived from the Brown / Lugo model (Table 3.1). Fearnside (1992a) sums up adjustments he uses in his model as a 27.87% net adjustment for live above ground components and an additional 9.03% for dead aboveground components applied to the adjusted live TAGB. Among the live aboveground adjustments to aboveground biomass of trees $\geq$ 10 cm dbh by Fearnside (1992a) are 4.25% for vines, 0.21% for "other" non-tree components, 3.50% for palms, and 12.00% for trees$\leq$10 cm dbh for a total of 19.96%. In our study the total mean percentage of aboveground biomass of trees $\geq$ 10 cm dbh for the aforementioned components were; 0.2% vines, 0.2% "other", 8.1% palms, and 5.2% trees < 10 cm dbh in open forests; 0.2% vines, 0.2% "other", 5.6% palms, and 4.8% trees < 10 cm dbh for dense forests; 0.2% vines, 0.1% "other", 18.0% palms, and 3.9% trees < 10 cm dbh in ecotone forest respectively(Chapter 2, Appendix A.1). In our data proportions of contributions from vegetative components other than trees $\geq$ 10 cm dbh are different from those

of Fearnside (1992a) giving an overall contribution of 13.67%, 10.74 % and 22.20% for open, dense and ecotone forests respectively. This contribution is lower in open (6.29%) and dense (9.22%) forests but higher in ecotone forests (2.24%) compared to the 19.96 % Fearnside adjustment. The mean for coarse wood debris, standing dead and litter/rootmat combined from our study had contributions of 15.6%, 9%, and 9.5% of the TAGB for open, dense, and ecotone forests respectively (Chapter 2, Figure 2.5). The mean for coarse wood debris, standing dead and litter/rootmat combined in our field measurements confirms the Fearnside correction factor for the dense and ecotone forest but is 5 % higher in the open forest. The additional adjustment factors for bark, sapwood, and form factor totals 7.9%of aboveground biomass of trees $\geq$ 10 cm dbh (Fearnside 1992a). These adjustments were unnecessary for our data because we used an individual tree model taken from direct measurements which encompassed all the aforementioned factors.

Considering the discrepancies between factors used in the 2 models and the information from our study it is surprising that the grand means are not more disparate. This is probably reflective of the heterogeneity of the Amazonian tropical forests and more importantly the way the model estimates over-estimate and under-estimate biomass depending on forest type effectively canceling out the error in each.

Comparison of TAGB area weighted means from the Fearnside model, Brown / Lugo model and TAGB estimates from this study

Each site identified in RADAMBRASIL may be generally composed of 2 or more forest types but they are lumped into a dominant forest type for the purpose of statistical analysis (DNPM, vol 16, 1978). Forests that are classified as open on maps at a scale of 1:1,000,000 may contain large areas classified as dense at a scale of 1:250,000 (Brown, I.F., et al., 1995). It has been suggested that biomass estimates could be improved by linking maps of forest types with data on biomass for each type based on geographic information systems (GIS) (I.F. Brown et al., 1995, Fearnside 1992b). The weighted mean uses land area in each forest classification to determine a more accurate biomass estimate for a given area.

The differences in mean biomass by forest type between the RADAMBRASIL based model estimates and field data becomes more critical at the larger scale. The weighted mean for the Brown / Lugo model, 278.4 Mg ha^{-1}, was similar to that reported in Brown and Lugo (1992) of 252 $\pm$32 Mg ha^{-1} for dense forests. The weighted mean for the Fearnside estimate of 388.2 Mg ha^{-1} was higher than the value of 334.9 Mg ha^{-1} (394 Mg ha^{-1} less 15% for below ground biomass) reported by Fearnside as the mean for all Amazonian forests (1992b). The predicted biomass pools of the area covered in RADAMBRASIL vol. 16 Porto Velho dramatically varied depending upon model selection (Table 3.6). The Fearnside estimate was 1.2 Pg (17%) larger than the estimate from this study and the Brown / Lugo model estimate was 1.1 Pg (16%) less than the field data.

There can also be a difference dependent on how the land area is broken up into classification units. The area weighted estimate based on subregion means is limited by our sample to 80% of the forested area by using the coarser resolution of forest type - regional mean we can extend our area weighted estimate to 100% of the forested area. The difference in the results from the weighted mean by the subregion and the weighted mean by forest type is mostly due to the larger land area represented by the forest type mean. The remainder of the difference is due to the fact that the open forest make up 62.8 % of the land cover for the region and therefore contribute more influence on the weighted mean. The Brown / Lugo and Fearnside models both yielded higher biomass estimates for open forests than dense forests which results in a weighted mean that is higher than if the same models were used on dense forests alone.

The 3,000 km arc of deforestation in the Brazilian Amazon runs along the southern edge of the Legal Amazon and northward through the eastern Amazon (Fearnside 1990). The state of Rondônia falls within the path of the deforestation arc. The estimate of deforestation in Rondônia ranges from 11.5% (Skole et al, 1994) to 20% (Fearnside, 1992b) of the original forested area. Open forests make up 62.8 % of Rondônian forests, dense forests account for 17.5% and ecotone types are 13.9% (Table 3.4, from the DNPM, 1978). If deforestation estimates for Rondônia are accurate then 30,142 to 52,422 km^2 of the original forests have been cut and burned. This would represent a total of 1.00 to 1.75 Pg of forest biomass effected by deforestation (calculated using the weighted mean from our data). A majority of the deforestation in Rondonia is occurring in non-dense forests (open

and ecotone). Depending on the model utilized as well as how the forest types are classified and how biomass is apportioned among the forest area the estimation of biomass lost in deforestation and consequently carbon flux can dramatically vary from 0.76 Pg to 2.07 Pg (using the Brown and Lugo, (1992) biomass estimate and the Fearnside (1992a) estimate respectively, with the given deforestation estimates).

If the rate of deforestation in the entire Amazon Basin is 20 x 10^3 km^2 yr^{-1} (up to 1988; Skole, 1994) and we assume that deforestation occurs in the individual forest types in proportion to the area covered by those forest types in the arc of deforestation (36% open forest, 38% dense forests and 25% ecotone forests (calculated from Table 5; Fearnside (1992b) for the states of Acre, Marranhao, Mato Grasso, Para, Rondonia, and Tocantins). Then we estimate that deforestation influenced 0.7000 Pg of biomass yr^{-1} (7.000 Pg over 10 years) effecting 0.350 Pg C yr^{-1} (3.500 Pg C over 10 years) (based upon weighted mean TAGB by forest type estimates from this study, Table 3.6). Calculating the C effected over the same area using the weighted mean from the Brown / Lugo and Fearnside models gives 2.780 and 3.877 Pg respectively, over 10 years, a difference of 20% and 11% respectively from our projection.

Total C flux from low latitude forests in the neotropical Americas is estimated to range between 0.5 to 0.7 Pg yr^{-1} (Dixon et al, 1994), (i.e.; the Amazonian deforestation was 50% to 70% of the C). If the Brown / Lugo model grand mean is used the C content of the biomass is 0.2778 Pg yr^{-1} (or 40% to 56 % of the total C). Calculations using the Fearnside model grand mean the value is 0.3860 Pg C yr^{-1} (or 55% to 78% of the total C). The method and model used for

biomass calculations has an increasing magnitude of effect as the scale and time period is increased.

Correlation of RADAMBRASIL tree density and commercial volume to TAGB and tree density derived from this study.

Use of the RADAMBRASIL forest inventory to accurately estimate TAGB is questionable. Lack of a relationship between our field data (i.e., tree density $\geq$ 30 cm dbh, aboveground biomass of trees $\geq$30 cm dbh or TAGB) to RADAMBRASIL tree density or commercial volume estimates indicates that we cannot quantify a relationship of aboveground biomass to data presented in RADAMBRASIL. Therefore, no model based on the RADAMBRASIL commercial volume data was possible. Reasons for the lack of correlation in results may partially lie in the purpose of, and the conditions under, which the RADAMBRASIL project was carried out. The primary purpose of RADAMBRASIL was to inventory commercially valuable timber resources. Less attention was given to trees and vegetation components that were without commercial value. Brown, I. F. (et al.,1995) reports a personal communication from N. Rosa (1993), revealing that bole and tree height in many RADAMBRASIL inventories were estimated by eye. Field conditions for the teams carrying out the inventory were difficult, dangerous, and sometimes fatal. Although there was some air support to get to remote locations, for the most part the teams (as were we) were restricted to areas that could be accessed by river, road, or trail. Lumping of sites that contained several forest types into one classification for summary data loses a level of resolution in

the data, but indicates the high degree of heterogeneity in the tropical moist forest. Commercial volume reported only for trees $\geq$30 cm dbh leaves room for error in estimation of biomass for size classes < 30 cm dbh for which there is no data.

Commercial volume also failed to give information on a portion of the TAGB in other vegetation components, (trees $\leq$ 30 cm dbh, palm, dead wood and forest floor that can be as high as 40 to 47%) of the TAGB (Chapter 2, Appendix A.1). The vast amount of information reported in RADAMBRASIL is impressive and valuable for many purposes (soil classification; delineation of vegetation cover types, species distribution, geology and geomorphology) but the tree commercial volume can not reliably translate to TAGB. It is, however, possible that the use of the RADAMBRASIL mapping of forest classification and area could be useful in improving TAGB estimates throughout the Legal Amazon (as the IBDF (Brazilian Institute for Forest Development)and IBGE (Brazilian Institute for geography and Statistics) maps were used by Fearnside for his calculations of TAGB for the Amazon (1992b, Table 12).

Chapter 4

Conclusions

Results of this study to quantify total above ground biomass (TAGB) and structure of Amazonian tropical forests delineated by RADAMBRASIL in northern Rondônia, Brazil led to the following conclusions:

- Mean TAGB by forest type was; open forests - 314 Mg ha^{-1} , dense forest - 377 Mg ha^{-1} and ecotone forests - 350 Mg ha^{-1} . Area weighted mean for 80% of the state of Rondônia by forest type and geomorphic subregion was 332 Mg ha^{-1}.
- Range of TAGB in open forest was less than that of dense or ecotone forests (288 to 345 Mg ha^{-1} vs. 298 to 534 Mg ha^{-1} and 298 to 422 Mg ha^{-1} , respectively). The only subregion that was significantly different from the others was the dense, lowhills of southern Amazonia which accounts for 6% of the vegetation cover in the study area.
- Contribution of non-tree components to TAGB varied from 7% to 40%. Major non-tree components were palm and the combined dead wood and forest floor. Non-tree component comprised a slightly higher proportion of TAGB in open and ecotone forests compared to dense forests (Averaging 19%, 21% and 16% respectively.
- Trees 10 to 50 cm dbh contributed slightly more proportionally to the TAGB in open forest than in dense or ecotone forests. The 10 to 50 cm dbh classes

contributed 47%, 42% and 38 % to the TAGB in open, dense, and ecotone forest respectively.

- Greatest variation in tree biomass among forest types was in the ≥ 50 cm dbh size classes. In open forests trees ≥ 50 cm dbh averaged 92 Mg ha^{-1}; in dense forests 158 Mg ha^{-1}; and in ecotone forests 137 Mg ha^{-1}.
- There were no trees ≥ 200 cm dbh in any of the open forest sites, dense forest had trees ≥ 200 cm dbh in 43% of the sites and ecotone forests in 50%.
- Major differences in the structure of tree biomass was in trees ≥ 70 cm dbh which made up 18% of the biomass in trees ≥ 10 cm dbh in open forests, 31% in dense forests and 41% in ecotone forests.
- Density of trees 10 - 30 cm dbh was similar among open and dense forests (358 and 379 ha^{-1}, respectively, within 6%of each other). This is contrary to an assumption of fewer trees 10 - 30 cm dbh in dense forest that is used in formulating the Brown and Lugo (1992) model to estimate biomass using the RADAMBRASIL forest inventory.
- The proportion of biomass in trees ≥30 cm dbh as compared to biomass of trees ≥ 10 cm dbh was similar among forest types (68%,in open forests; 72%, in dense forests; and 75%, in ecotone forests). The fraction of the total volume of trees ≥ 10 cm dbh represented by trees ≥ 30 cm dbh was assumed to be lower in open forests as compared to dense forests (Brown and Lugo, 1992). If the proportion of biomass can be assumed to be directly

correlated to volume than the assumption of a lower proportion of biomass represented in trees $\geq$ 30 cm dbh was exaggerated for open forests.

- Quadratic stand diameters (QSD) for trees $\geq$ 10 cm dbh were similar among forest types (25 cm, in open forests; 27 cm, in dense forests; and 27 cm in ecotone forests). The Brown and Lugo (1992) model for estimating biomass from the RADAMBRASIL inventory data assumes that the dense forests will have a higher QSD (> 30 cm) than open forest. Therefore the volume expansion factor (VEF) for open forests is-over-estimated. The error in the VEF resulted in an over-estimate of open forest biomass compared to dense forest biomass.
- The Fearnside (1992b) estimates are based on the Brown and Lugo (1992) estimates of biomass and so carry over the errors from that model.
- There was no correlation between our TAGB or tree density and RADAMBRASIL forest inventory commercial volume or tree density. Therefore, no model was possible.
- Despite errors in model assumptions and the lack of correlation between field measurements and RADAMBRASIL data the weighted mean TAGB estimates from the 2 models were close to that derived in our study. This was probably due to the over-estimation of open forests biomass balancing out the under-estimation of dense forests biomass in each commercial volume model.

A valid prediction of carbon flux for the vast forest areas of the Legal Amazon will require more detailed descriptions of deforestation delineated by

forest type as Fearnside (1992b) has done. Estimates used for TAGB effect estimates of carbon pools in tropical forest. Vegetative sources of carbon are effected differently by deforestation and release carbon at different rates. Therefore, components of biomass included or excluded from estimates are important factors when determining the fate of C from deforestation projected over large scales of time and space.

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Appendix

Appendix A.1. Proportion of the biomass of trees > 10 cm dbh in selected biomass components from 20 RADAMBRASIL forest inventory sites.

Forest type - Region	Geomorphic - Subregion	plot	The percentage of above ground biomass for trees > 10 cm dbh in each component of TAGB.										
			Seedlings & vines	Palms	Forest floor	Coarse wood debris	Trees < 10 cm dbh	Trees 10 - 30 cm dbh	Trees 30 - 50 cm dbh	Trees 50 - 70 cm dbh	Trees 70 - 100 cm dbh	Trees 100-200 cm dbh	Trees 200 - 300 cm dbh
Open tropical forest	Amazon alluvial	225	0.28	46.3	4.0	7.0	3.1	26.1	34.2	35.1	4.6	0.0	0.0
		226	0.20	1.6	7.1	12.9	7.7	38.1	40.4	18.3	3.1	0.0	0.0
	Broken surface of the Upper Xingu / Tapajos / Madeira	70	0.66	2.8	4.3	24.4	4.7	30.4	31.1	10.7	6.7	21.0	0.0
		74	0.26	3.3	4.8	18.5	8.1	34.9	27.4	12.5	9.8	15.4	0.0
		75	1.08	0.6	3.1	11.5	6.3	31.1	25.9	23.5	2.7	16.8	0.0
		76	0.12	3.5	3.1	14.7	3.8	25.5	18.6	25.9	2.7	27.4	0.0
		89	0.12	2.9	4.0	7.0	5.8	36.5	26.3	14.1	12.1	11.1	0.0
		113	0.15	3.7	3.7	9.8	2.9	31.3	35.9	19.1	0.0	13.6	0.0
	Mean		0.36 ± 0.14	8.1 ± 5.5	4.3 ± 0.5	13.2 ± 2.1	5.2 ± .7	31.7 ± 1.6	30.0 ± 2.4	19.9 ± 2.8	5.2 ± 1.4	13.2 ± 3.4	0.0
Dense tropical forest	Amazon alluvial	1	0.21	3.0	1.3	3.4	6.8	17.3	11.7	3.4	21.0	5.0	41.6 0
		2	0.31	3.0	1.9	4.3	3.1	22.6	30.0	29.2	18.2	0.0	0.0
	Low plates Amz.	229	0.43	1.0	6.9	23.0	6.6	49.1	29.3	9.4	4.5	7.7	0.0
	Low hills of Southern Amz.	24	1.27	5.2	2.8	5.6	2.1	15.3	18.4	21.7	6.1	16.8	21.7
		25	0.16	7.4	2.5	11.5	1.8	17.8	14.6	17.0	19.6	0.0	31.0
	Pre-Cambrian platform cover	43	0.45	16.8	2.5	6.9	5.0	33.5	39.3	13.4	13.9	0.0	0.0
		44	0.76	2.8	2.4	22.5	8.1	43.1	30.5	9.6	16.7	0.0	0.0
	Mean		0.37 ± 0.10	5.6 ± 2.0	2.9 ± 0.7	11.0 ± 3.2	4.8 ± .9	28.4 ± 3.8	24.8 ± 3.8	14.8 ± 3.3	14.3 ± 2.5	4.2 ± 2.4	13.5 ± 6.7
Areas of ecological tension	Savanna / forest edge	186	0.28	18.7	2.2	4.5	5.0	17.8	20.3	4.5	5.4	19.9	32.1
		188	0.25	73.3	5.1	23.5	2.4	24.5	29.6	10.3	21.7	14.0	0.0
		190	0.13	0.2	4.3	4.8	4.8	24.8	18.9	9.8	12.1	16.5	18.0
		195	0.82	9.9	2.7	4.8	3.3	34.2	30.8	8.8	10.8	15.4	0.0
	Mean		0.37 ± 0.20	18.0 ± 9.2	3.6 ± 0.7	9.4 ± 4.7	3.9 ± .6	25.3 ± 6.4	24.9 ± 3.1	8.3 ± 1.3	12.5 ± 3.4	16.4 ± 1.3	12.5 ± 7.8
Others	Anthropogenic	218	0.27	10.5	6.9	10.6	4.5	28.9	29.1	19.9	9.1	13.0	0.0
Grand mean			0.36 ± .073	9.32 ± 2.9	3.8 ± .4	11.6 ± 1.6	4.8 ± .4	29.2 ± 1.9	27.1 ± 1.7	15.8 ± 1.8	10.0 ± 1.5	10.7 ± 1.9	7.2 ± 3.0

Appendix A.2. Biomass of live trees from 20 RADAMBRASIL forest inventory sites. Units are in Mg ha^{-1}.

Forest type - Region	Geomorphic - Subregion	plot	Trees < 10 cm dbh	Trees 10 to 30 cm dbh	Trees 30 to 50 cm dbh	Trees 50 to 70 cm dbh	Trees 70 to100 cm dbh	Trees 100 to 200 cm dbh	Trees 200 to 300 cm dbh	Tree TAGB
Open tropical forest	Amazon alluvial	225	6.4 ± 2.2	53.2	70.0	71.7	9.4	0.0	0.0	210.7
		226	15.8 ± 2.1	84.9	90.1	40.8	7.0	0.0	0.0	238.5
	Broken surface of the Upper Xingu / Tapajos / Madeira	70	12.0 ± 2.9	76.8	78.6	27.1	16.9	53.0	0.0	264.3
		74	17.7 ± 3.3	75.8	59.6	27.1	21.4	33.5	0.0	235.0
		75	16.0 ± 3.2	79.1	65.8	59.7	6.9	42.8	0.0	270.2
		76	9.4 ± 2.6	63.3	46.1	64.1	6.7	67.9	0.0	257.4
		89	14.5 ± 4.1	91.1	65.7	35.2	30.2	27.7	0.0	264.4
		113	7.6 ± 1.8	83.4	95.7	50.9	0.0	36.3	0.0	273.8
	Mean		13.7 ± 1.5	76.0 ± 4.3	71.4 ± 5.7	47.1 ± 6.1	12.3 ± 3.5	32.6 ± 8.4	0.0 ± 0	251.8 ± 7.7
Dense tropical forest	Amazon alluvial	1	24.1 ± 3.7	61.6	41.6	11.9	74.5	17.7	148.0	379.5
		2	8.8 ± 3.0	64.1	85.0	82.9	51.5	0.0	0.0	292.3
	Low plates of Amaz.	229	14.2 ± 2.6	106.6	63.7	20.4	9.7	16.7	0.0	231.3
	Low hills of Southern Amazonia	24	9.8 ± 1.81	70.6	84.4	99.7	28.1	77.3	100.0	469.9
		25	6.6 ± 2.1	63.8	52.2	60.8	70.2	0.0	110.9	364.5
	Pre-Cambrian platform cover	43	11.3 ± 2.2	75.8	88.9	30.4	31.4	0.0	0.0	237.9
		44	20.0 ± 2.7	106.3	75.3	23.7	41.2	0.0	0.0	266.4
	Mean		13.5 ± 2.4	78.4 ± 7.5	70.2 ± 6.9	47.1 ± 12.9	43.8 ± 8.8	16.0 ± 6.0	51.3 ± 24.8	320.2 ± 33.2
Areas of ecological tension (Ecotone)	Savanna / forest edge	186	13.3 ± 3.1	47.5	54.0	12.0	14.4	53.0	85.5	279.7
		188	4.1 ± 1.2	41.8	50.5	17.5	36.9	23.8	0.0	174.6
		190	17.6 ± 2.7	91.7	69.7	36.2	44.7	60.8	66.4	387.1
		195	9.2 ± 4.3	93.6	84.3	24.1	29.5	42.2	0.0	282.8
	Mean		11.0 ± 2.9	68.6 ± 13.9	64.6 ± 7.8	22.5 ± 5.2	31.4 ± 6.5	45.0 ± 8.0	38.0 ± 22.3	281.1 ± 43.4
Others	Anthropogenic	218	9.8 ± 2.7	62.6	63.0	43.2	19.7	28.1	0.0	226.3
Grand mean			12.4 ± 1.1	74.7 ± 4.0	69.2 ± 3.5	42.0 ± 5.5	27.5 ± 4.7	29.0 ± 5.6	25.5 ± 10.6	280.3 ± 19.7

Appendix A.3. Biomass of live non-tree vegetation from 20 RADAMBRASIL forest inventory sites. Units are Mg ha^{-1}.

Forest type - Region	Geomorphic - Subregion	plot	Seedlings	Basal leaf palms	Palms < 10 cm dbh	Palms > 10 cm dbh	Vines < 10 cm dbh	Vines > 10 cm dbh	Living non-tree Vegetation
Open tropical forest	Amazon alluvial	225	0.6 ± 0.1	2.2 ± 0.4	0.1 ± 0.1	92.3	0.0 ± 0.0	0.0	95.2
		226	0.4 ± 0.1	0.7 ± 0.2	0.9 ± 0.4	1.9	0.0 ± 0.0	0.0	3.9
	Broken surface of the Upper Xingu / Tapajos / Madeira	70	0.7 ± 0.1	1.2 ± 0.3	0.3 ± 0.2	5.6	0.1 ± 0.0	0.9	8.7
		74	0.3 ± 0.0	3.0 ± 0.4	1.6 ± 0.4	2.5	0.2 ± 0.1	0.0	7.7
		75	0.3 ± 0.0	0.5 ± 0.2	0.9 ± 0.5	0.1	2.4 ± 2.4	0.0	4.2
		76	0.3 ± 0.1	0.9 ± 0.2	0.4 ± 0.3	7.3	0.0 ± 0.0	0.0	8.9
		89	0.3 ± 0.0	0.5 ± 0.2	0.0 ± 0.0	6.8	0.1 ± 0.0	0.0	7.7
		113	0.4 ± 0.0	1.5 ± 0.3	0.1 ± 0.1	8.3	0.1 ± 0.0	0.0	10.3
	Mean		0.4 ± 0.1	1.3 ± 0.3	0.6 ± 0.2	15.6 ± 11.0	0.4 ± 0.3	0.1 ± 0.1	18.3 ± 11.0
Dense tropical forest	Amazon alluvial	1	0.7 ± 0.1	0.0 ± 0	0.2 ± 0.1	10.4	0.1 ± 0.0	0.0	11.4
		2	0.5 ± 0.1	1.1 ± 0.4	0.0 ± 0	7.3	0.1 ± 0.0	0.3	9.3
	Low plates of Amazonia	229	0.3 ± 0.0	0.8 ± 0.2	1.1 ± 0.4	0.4	0.1 ± 0.0	0.6	3.3
	Low hills of Southern Amazonia	24	0.4 ± 0.1	0.6 ± 0.2	0.6 ± 0.3	22.7	0.0 ± 0.0	0.8	25.1
		25	0.5 ± 0.1	1.1 ± 0.3	0.9 ± 0.6	24.6	0.1 ± 0.1	0.0	27.2
	Pre-Cambrian platform cover	43	0.6 ± 0.1	1.5 ± 0.3	0.1 ± 0.0	36.4	0.1 ± 0.1	0.3	39.0
		44	0.3 ± 0.1	0.9 ± 0.3	0.5 ± 0.2	5.5	0.1 ± 0.0	1.5	8.7
	Mean		0.5 ± 0.1	0.8 ± 0.2	0.5 ± 0.2	15.3 ± 4.9	0.1 ± 1.1	0.5 ± 0.2	17.7 ± 4.9
Areas of ecological tension (Ecotone)	Savanna / forest edge	186	0.3 ± 0.	0.8 ± 0.3	3.1 ± 1.0	46.0	0.0 ± 0.0	0.4	50.6
		188	0.4 ± 0.1	2.1 ± 0.2	0.3 ± 0.2	71.5	0.0 ± 0.0	0.0	74.3
		190	0.5 ± 0.0	0.0 ± 0	0.0 ± 0	0.8	0.0 ± 0.0	0.0	1.3
		195	0.3 ± 0.0	2.2 ± 0.3	1.01 ± 0.4	23.8	0.1 ± 0.0	1.9	29.3
	Mean		0.4 ± 0.0	1.3 ± 0.5	1.1 ± 0.7	35.5 ± 15.1	0.0 ± 0.0	0.6 ± 0.5	38.9 ± 15.5
Others	Anthropogenic	218	0.4 ± 0.1	0.7 ± 0.2	0.8 ± 0.5	21.2	0.1	0.0	23.3
Grand mean			0.41 ± 0.0	1.1 ± 0.2	0.7 ± 0.2	19.8 ± 5.6	0.2 ± 0.1	0.3 ± 0.1	22.5 ± 5.6

Appendix A.4. Coarse wood debris (CWD), standing dead and forest floor (litter and rootmat) from 20 RADAMBRASIL forest inventory sites. Units are in Mg ha^{-1}.

Forest type - Region	Geomorphic - Subregion	plot	Forest floor	Coarse wood debris	Dead palm	Dead vine < 10 cm dbh	Dead Trees < 10 cm dbh	Dead trees 10-30 cm dbh	Dead Trees > 30 cm dbh	Aboveground biomass of CWD and standing dead
Open tropical forest	Amazon alluvial	225	8.1 ± 2.3	14.4 ± 7.4	0.29	0.00 ± 0	0.0 ± 0	0.00	0.03	14.7
		226	15.8 ± 1.6	28.7 ± 9.3	0.11	0.00 ± 0	1.0 ± .6	0.02	0.06	30.7
	Broken surface of the Upper Xingu / Tapajos / Madeira	70	11.0 ± 0.9	61.5 ± 23.8	0.02	0.00 ± 0	0.1 ± .0	0.00	0.07	61.7
		74	10.5 ± 1.5	40.2 ± 19.7	0.00	0.00 ± 0	1.1 ± .8	0.13	0.04	41.5
		75	7.8 ± 2.0	29.2 ± 15.6	0.00	0.00 ± 0	0.0 ± 0	0.01	0.11	29.3
		76	7.6 ± 0.7	36.5 ± 15.9	0.00	0.00 ± 0	0.1 ± .1	0.07	0.25	36.9
		89	9.9 ± 1.0	17.4 ± 6.1	0.00	0.01 ± .01	0.1 ± .1	0.01	0.02	17.5
		113	9.8 ± 1.3	26.2 ± 11.5	0.00	0.00 ± 0	0.8 ± .7	0.00	0.06	27.1
	Mean		10.1 ± 0.9	31.8 ± 5.2	0.05 ± .04	0.00 ± .00	0.3 ± .1	0.03 ± 0.0	0.08 ± 0.03	32.4 ± 5.2
Dense tropical forest	Amazon alluvial	1	4.6 ± 0.6	12.2 ± 5.9	0.00	0.00 ± 0	0.0 ± 0	0.00	0.00	12.3
		2	5.3 ± 0.7	12.2 ± 5.7	0.00	0.00 ± 0	0.0 ± 0	0.00	0.02	12.3
	Low plates of Amazonia	229	15.1 ± 2.3	49.9 ± 16.9	0.00	0.00 ± 0	0.1 ± .0	0.01	0.05	50.0
	Low hills of southern Amazonia	24	12.8 ± 0.7	25.7 ± 14.5	0.00	0.00 ± 0	0.4 ± .4	0.02	0.02	26.1
		25	8.8 ± 1.0	41.3 ± 19.2	0.00	0.00 ± 0	0.0 ± 0	0.02	0.03	41.3
	Pre-Cambrian platform cover	43	5.5 ± 0.5	15.7 ± 6.9	0.02	0.00 ± 0	0.0 ± 0	0.00	0.00	15.7
		44	5.9 ± 0.6	55.4 ± 30.7	0.00	0.00 ± 0	0.1 ± .1	0.01	0.04	55.5
	Mean		8.3 ± 1.6	30.3 ± 6.9	0.00 ± .00	0.00 ± 0	0.1 ± .0	0.01 ± 0.0	0.02 ± 0.01	30.5 ± 6.9
Areas of ecological tension (Ecotone)	Savanna / forest edge	186	5.9 ± 0.7	12.1 ± 4.7	0.00	0.00 ± 0	0.0 ± .0	0.01	0.00	12.1
		188	8.8 ± 1.4	40.0 ± 15.2	0.12	0.00 ± 0	0.0 ± .0	0.00	0.02	40.2
		190	16.1 ± 4.9	17.6 ± 9.5	0.00	0.00 ± 0	0.2 ± .1	0.00	0.01	17.7
		195	7.3 ± 1.1	13.1 ± 5.9	0.00	0.00 ± 0	0.0 ± 0	0.00	0.03	13.2
	Mean		9.5 ± 2.3	20.7 ± 6.6	0.03 ± .03	0.00 ± 0	0.1 ± .1	0.01 ± 0.0	0.02 ± 0.01	20.8 ± 6.6
Others	Anthropogenic	218	14.8 ± 2.2	22.9 ± 12.2	0.00	0.00 ± 0	0.0 ± 0	0.02	0.01	22.9
Grand mean			9.6 ± 0.8	28.6 ± 3.4	0.03 ± .02	0.00 ± .00	0.2 ± .1	0.02 ± .00	0.04 ± 0.01	28.9 ± 3.4

Appendix A.5. Density of trees by diameter classes, live and standing dead from 20 RADAMBRASIL forest inventory sites. Units are individuals ha^{-1}.

Forest Type - Region	Geomorphic - Subregion	plot	Trees < 10 cm dbh (*100)	Trees 10 - 30 cm dbh	Trees 30 - 50 cm dbh	Trees 50- 70 cm dbh	Trees 70 - 100 cm dbh	Trees 100 -200 cm dbh	Trees 200 - 300 cm dbh	Dead trees < 10 cm dbh	Dead trees 10 - 30 cm dbh	Dead trees > 30 cm dbh
Open tropical forest	Amazon alluvial	225	23±5	221.0	50.79	17.78	1.27	0.00	0.00	0±0	0	8
		226	95±7	392.4	68.57	12.70	1.27	0.00	0.00	1±91	38	20
	Broken surface of the Upper Xingu / Tapajos / Madeira	70	83±1	339.1	54.60	7.62	2.54	3.81	0.00	188±101	30	8
		74	94±8	400.0	44.44	8.89	2.54	2.54	0.00	94±56	57	5
		75	92±8	392.4	46.98	17.78	1.27	1.27	0.00	31±31	11	10
		76	75±1	304.8	36.83	17.78	1.27	5.08	0.00	31±31	30	8
		89	61±7	464.8	46.98	10.16	3.81	1.27	0.00	125±72	27	5
		113	75±8	361.9	66.03	15.24	0.00	2.54	0.00	188±126	23	15
	Mean		75±8	359.5±25.8	51.90±3.82	13.49±1.50	1.75±.41	2.06±.63	0.00±.00	82±27	27±6	10±2
Dense tropical forest	Amazon alluvial	1	48±5	384.8	30.48	2.54	8.89	1.27	2.54	0±0	15	1
		2	26±5	308.6	60.95	24.13	7.62	0.00	0.00	31±31	8	4
	Low plates of	229	88±9	464.8	54.60	6.35	1.27	1.27	0.00	125±43	34	15
	Low hills of Southern Amaz.	24	52±5	316.2	55.87	27.94	3.81	2.54	1.27	94±68	8	3
		25	41±6	323.8	36.83	16.51	8.89	0.00	1.27	94±50	23	6
	Pre-Cambrian platform cover	43	60±4	388.6	62.22	8.89	3.81	0.00	0.00	125±62	27	1
		44	91±8	464.8	55.87	7.62	5.08	0.00	0.00	63±62	19	8
	Mean		58±9	378.8±25.2	50.98±4.65	13.42±3.64	5.62±1.10	0.73±.38	0.73±.38	76±21	19±4	5±2
Areas of ecological tension	Savanna / forest edge	186	56±8	270.5	39.37	3.81	2.54	2.54	1.27	125±72	23	10
		188	20±3	175.2	36.83	5.08	5.08	1.27	0.00	31±31	15	3
		190	94±1	403.8	53.33	10.16	6.35	2.54	1.27	156±88	8	3
		195	28±3	411.4	63.49	7.62	3.81	1.27	0.00	0±0	8	9
	Mean		49±1	315.2±56.8	48.25±6.24	6.67±1.41	4.44±.82	1.90±.36	0.63±.36	78±37	13±3	6±2
Others	Anthropogenic	218	61±5	224.8	49.52	11.43	2.54	1.27	0.00	63±43	11	3
Grand mean			63±6	350.7±18.5	50.73±2.42	12.00±1.50	3.68±.58	1.52±.31	0.38±.16	78±14	21±3	7±1

Appendix A.6. Density for each non-tree vegetation component from 20 RADAMBRASIL forest inventory sites. Units are individuals ha^{-1}.

Forest Type - Region	Geomorphic - Subregion	plot #	Seedling (times 1000)	Basal leaf palms	Palm < 10 cm dbh	Palm > 10 cm dbh	Vine < 10 cm dbh	Vines > 10 cm dbh	Dead Palms < 10 cm dbh	Dead vine < 10 cm dbh
Open tropical forest	Amazon alluvial	225	249 ± 42	1406 ± 242	31 ± 31	171	250 ± 91	0.00	63 ± 62	0 ± 0
		226	188 ± 26	469 ± 96	250 ± 91	15	1625 ± 407	0.00	31 ± 31	0 ± 0
	Broken surface	70	287 ± 42	688 ± 176	344 ± 134	107	1844 ± 471	11.43	0 ± 0	0 ± 0
	of the Upper	74	151 ± 19	1563 ± 232	531 ± 148	27	5594 ± 1273	0.00	0 ± 0	0 ± 0
	Xingu / Tapajos /	75	138 ± 17	313 ± 100	219 ± 111	11	3125 ± 937	0.00	0 ± 0	0 ± 0
	Madeira	76	113 ± 14	500 ± 120	94 ± 68	65	3000 ± 309	0.00	0 ± 0	0 ± 0
		89	109 ± 15	313 ± 136	63 ± 62	23	1875 ± 615	0.00	0 ± 2	31 ± 31
		113	153 ± 18	781 ± 170	94 ± 68	61	1719 ± 420	0.00	0 ± 0	0 ± 0
	Mean		174 ± 23	754 ± 170	203 ± 60	60 ± 19	2379 ± 557	1 ± 1.4	12 ± 8.3	4 ± 3.9
Dense tropical forest	Amazon alluvial	1	307 ± 37	0 ± 0	156 ± 88	114	2125 ± 466	0.00	0 ± 0	0 ± 0
		2	210 ± 29	563 ± 198	0 ± 0	160	3156 ± 744	3.81	0 ± 0	63 ± 63
	Low plates of	229	107 ± 16	438 ± 110	406 ± 152	4	3594 ± 445	7.62	0 ± 0	31 ± 31
	Low hills of	24	174 ± 36	313 ± 111	125 ± 72	42	1188 ± 285	7.62	0 ± 0	0 ± 0
	Southern Amaz.	25	219 ± 30	594 ± 146	188 ± 77	130	1750 ± 449	0.00	0 ± 0	0 ± 0
	Pre-Cambrian	43	278 ± 36	781 ± 151	94 ± 68	202	2250 ± 413	3.81	0 ± 0	0 ± 0
	platform cover	44	139 ± 25	406 ± 123	406 ± 166	30	3438 ± 476	8.89	0 ± 0	0 ± 0
	Mean		205 ± 27	442 ± 93	196 ± 58	97 ± 28	2500 ± 345	5 ± 1.5	0 ± 0	13 ± 9.4
Areas of ecological tension	Savanna / forest edge	186	131 ± 14	531 ± 185	1875 ± 462	130	1031 ± 675	3.81	0 ± 0	0 ± 0
		188	169 ± 30	1281 ± 151	219 ± 101	187	813 ± 258	0.00	0 ± 0	0 ± 0
		190	195 ± 19	0 ± 0	0 ± 0	8	1656 ± 508	0.00	0 ± 0	0 ± 0
		195	109 ± 17	1219 ± 164	438 ± 135	103	1281 ± 341	15.24	0 ± 0	0 ± 0
	Mean		151 ± 19	758 ± 304	633 ± 423	107 ± 37	1195 ± 181	5 ± 3.5	0 ± 0	0 ± 0
Others	Anthropogenic	218	171 ± 25	438 ± 143	188 ± 110	57	3531 ± 633	0.00	0 ± 0	31 ± 31
Grand mean			180 ± 14	630 ± 97	286 ± 90	82 ± 14	2242 ± 278	3 ± 1.1	5 ± 1.1	8 ± 3.8

Appendix A.7. Basal Area of trees from 20 RADAMBRASIL forest inventory sites. Units are in $m^2 ha^{-1}$.

Forest type - Region	Geomorphic - Subregion	plot	Trees < 10 cm dbh	Trees 10 to 30 cm dbh	Trees 30 to 50 cm dbh	Trees 50 to 70 cm dbh	Trees 70 to 100 cm dbh	Trees 100 to 200 cm dbh	Trees 200 to 300 cm dbh	Total Tree Basal Area
Open tropical forest	Amazon alluvial	225	1.60 ± .45	5.42	5.69	5.37	0.67	0.00	0.00	18.75
		226	4.31 ± .38	8.77	7.35	3.11	0.51	0.00	0.00	24.05
	Broken surface of the Upper Xingu / Tapajos / Madeira	70	3.36 ± .68	7.88	6.36	2.05	1.22	3.60	0.00	24.47
		74	4.52 ± .68	8.08	4.86	2.07	1.51	2.29	0.00	23.33
		75	4.42 ± .69	8.36	5.34	4.54	0.50	2.72	0.00	25.88
		76	2.65 ± .55	6.62	3.77	4.84	0.49	4.63	0.00	23.00
		89	3.83 ± .79	9.62	5.33	2.67	2.15	1.82	0.00	25.42
		113	2.35 ± .39	8.56	7.74	3.87	0.00	2.46	0.00	24.98
	Mean		3.38 ± 0.38	7.92 ± .46	5.81 ± .46	3.56 ± .45	0.88 ± .24	2.09 ± .57	0.00	23.74 ± .79
Dense tropical forest	Amazon alluvial	1	5.53 ± .73	6.95	3.39	0.88	5.27	1.21	8.97	32.20
		2	2.04 ± .58	6.77	6.90	6.28	3.70	0.00	0.00	25.69
	Low plates of Amaz.	229	3.85 ± .96	10.94	5.24	1.55	0.69	1.14	0.00	23.41
	Low hills of Southern Amazonia	24	2.71 ± .43	7.24	6.81	7.53	2.01	4.90	5.94	37.14
		25	1.64 ± .41	6.75	4.23	4.58	4.98	0.00	6.54	28.72
	Pre-Cambrian platform cover	43	2.94 ± .42	8.10	7.21	2.31	2.23	0.00	0.00	22.79
		44	4.88 ± .56	10.85	6.13	1.81	2.92	0.00	0.00	26.59
	Mean		3.37 ± 0.55	8.32 ± .71	5.70 ± .55	3.56 ± .97	3.11 ± .62	1.40 ± .68	3.06 ± 1.49	28.08 ± 1.90
Areas of ecological tension	Savanna / forest edge	186	3.31 ± .63	5.23	4.39	0.92	1.05	3.49	5.14	23.53
		188	1.12 ± .27	4.26	4.10	1.33	2.64	1.58	0.00	15.03
		190	4.68 ± .50	9.46	5.69	2.74	3.20	3.97	4.07	33.81
		195	2.14 ± .77	9.58	6.87	1.84	2.09	2.68	0.00	25.20
	Mean		2.81 ± 0.66	7.13 ± 1.39	5.26 ± .63	1.71 ± .39	2.25 ± .46	2.93 ± .52	2.30 ± 1.34	24.39 ± 3.85
Others	Anthropogenic	218	2.40 ± .54	6.15	5.15	3.25	1.40	1.84	0.00	20.19
Grand mean			3.22 ± .27	7.78 ± .40	5.63 ± .28	3.18 ± .41	1.96 ± .33	1.92 ± .36	1.53 ± .51	25.21 ± 1.12

Appendix A.8. Quadratic Stand Diameter by diameter class for trees from 20 RADAMBRASIL forest inventory sites. Units are in cm dbh.

Forest type - Region	Geomorphic - Subregion	plot	Quadratic Stand Diameter (QSD)	
			Trees > 10 cm dbh	Trees > 30 cm dbh
Open tropical forest	Amazon alluvial	225	27.40	46.24
		226	23.01	41.16
	Broken surface of the Upper Xingu / Tapajos / Madeira	70	25.68	49.56
		74	22.86	48.38
		75	24.32	49.59
		76	26.62	53.55
		89	22.84	49.49
		113	25.43	46.23
	Mean		24.77 ± 2.67	48.03 ± 1.28
Dense tropical forest	Amazon alluvial	1	28.08	74.11
		2	27.39	48.15
	Low plates of Amaz.	229	21.71	41.58
	Low hills of Southern Amazonia	24	32.79	61.53
		25	29.84	63.85
	Pre-Cambrian platform cover	43	23.35	44.69
		44	22.89	47.01
	Mean		26.57 ± 1.54	54.42 ± 4.58
Areas of ecological tension	Savanna / forest edge	186	28.36	62.08
		188	28.15	50.46
		190	27.87	58.31
		195	24.54	47.46
	Mean		27.23 ± 5.94	54.58 ± 3.39
Others	Anthropogenic	218	27.97	47.84
Grand mean			26.06 ± 0.65	51.56 ± 1.86

IV. Ecosystem structure in the Brazilian Cerrado: A vegetation gradient of aboveground biomass, Root mass and consumption by fire.

ECOSYSTEM STRUCTURE IN THE BRAZILIAN CERRADO: A VEGETATION GRADIENT OF ABOVEGROUND BIOMASS, ROOT MASS AND CONSUMPTION BY FIRE

Running title: Biomass and fire in the Brazilian Cerrado

Key words: aboveground biomass, Brazil, belowground biomass, Cerrado, fire ecology, fuels, root mass, tropical savanna.

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ABSTRACT

Conversion to permanent agriculture is rapidly occurring over vast areas of the 1.8 million km^2 Brazilian Cerrado; a region that is naturally a mosaic of grasslands, savannas, and evergreen tropical woodlands. Yet, few studies have quantified total biomass of plant communities in this ecosystem, particularly the belowground component; a C pool of potential global significance. Total biomass (aboveground and belowground), and the quantity of biomass consumed by fires were measured in four plant communities comprising a vegetation gradient from pure grassland (campo limpo) to a woodland with a closed canopy of tall shrubs and scattered trees (cerrado denso) near Brasilia, DF, Brazil. Total aboveground biomass (TAGB) increased along this gradient from 5.5 Mg ha^{-1} in campo limpo to 29.4 Mg ha^{-1} in cerrado denso. Vegetation structure varied among communities; trees were nonexistent in campo limpo, but were at a density of 1000 ha^{-1} and a biomass of 12.9 Mg ha^{-1} in cerrado denso. Fires consumed 92 and 84% of the TAGB in campo limpo (pure grassland) and campo sujo (savanna), respectively. In cerrado aberto and cerrado denso, trees and tall shrubs were little affected by fire. Combustion factors of the TAGB in these communities was 54 and 33%, respectively. The total biomass consumed by fire ranged from 5.0 Mg ha^{-1} in campo limpo to 13.5 Mg ha^{-1} in cerrado aberto. Compared to other widespread Brazilian ecosystems (tropical dry forest and evergreen forest), the Cerrado has a lower aboveground biomass. The TAGB of cerrado denso is <9% of that of Amazonian tropical evergreen forest. The total quantity of biomass consumed by fire, and hence emissions to the atmosphere is lower in intact Cerrado communities compared to fires in slashed tropical forest.

Total belowground biomass (TBGB) increased from 16.3 Mg ha^{-1} in campo limpo, to 30.1 Mg ha^{-1} in campo sujo, to 46.5 Mg ha^{-1} in cerrado aberto, and to 52.9 Mg ha^{-1} in cerrado denso. This quantity of belowground biomass is similar to, or exceeds that reported for many tropical dry and moist forests. More than 80% of the TBGB was found to occur in the upper 30 cm of the soil, except for cerrado denso (71%) where a greater proportion of tree roots were present at deeper levels. Root:shoot ratios were very high in all sites ranging from 2.9 in cerrado denso to 7.7 in campo sujo. Total ecosystem plant biomass (the total aboveground biomass and TBGB combined) ranged from 21.9 Mg ha^{-1} in campo limpo to 77.9 Mg ha^{-1} in cerrado denso. More than 71 % of the live phytomass (aboveground biomass + root biomass) is belowground in the Brazilian Cerrado. At current rates of land cover change in the Brazilian Cerrado, these ecosystem pools are likely significant sources of increasing atmospheric C and other greenhouse gasses.

INTRODUCTION

The Brazilian Cerrado is a tropical ecosystem containing a diverse mosaic of grasslands, savannas, woodlands and forests (Coutinho 1976). This ecosystem comprises 1.8 million km^2 in the central part of Brazil (Ab'Saber 1983), and fires and land conversion are widespread at present. However, few studies in the Cerrado have quantified total aboveground biomass (TAGB), or described the effects of fire in this ecosystem. Although the variability of fuel biomass, nutrient pools, fire behaviour and consumption in Cerrado communities were reported by Pivello & Coutinho (1992) and Kauffman *et al.* (1994), these studies did not include trees in their estimates of aboveground biomass.

In most ecosystems of the world, belowground structure and biomass have not received the same degree of study as the aboveground component (Russel 1977, Sanford 1989). This lack of information is related to the degree of difficulty and time associated with the methods of sampling, as well as the disturbance associated with destructive sampling approaches (Santantonio *et al.* 1977). Belowground tissues are poorly understood with respect to their function as ecosystem (and global) C pools. The relationship between increasing atmospheric CO_2, climate change, and accelerated rates of land use conversion in the tropics require better quantification of both the total aboveground and belowground biomass pools (Fearnside 1992). In tropical dry forests, total root biomass has been reported to range from 10 to 45 Mg ha^{-1} (Castellanos *et al.* 1991, Murphy & Lugo 1986). In three different forest community types of tropical evergreen forest in the Venezuelan Amazon, Sanford (1989) reported root biomass to range from 55 to 61 Mg ha^{-1}. In the eastern Amazon of Brazil (Para State), Nepstad (1989) found root biomass in an intact tropical rain forest and

a degraded grass/shrub community to be 35 and 10 Mg ha^{-1}, respectively. Murphy & Lugo (1986) reported a range in root biomass of 11-135 Mg ha^{-1} for tropical wet forests. In savanna and savanna woodlands of Africa and South America root biomass has been reported to range from 12-37 Mg ha^{-1} (Table 1). Even though the Cerrado is the second largest vegetation type in Brazil comprising 23% of the Country's land area (Eiten 1972) we could find no published studies where the belowground biomass of communities has been described.

The Brazilian Cerrado developed as a response to a history of frequent fires, nutrient poor soils, a deep water table, and a climate with marked wet and dry seasons (Eiten 1972). Eiten (1975) estimated the average frequency of fire set by indigenous people of the Cerrado in Mato Grosso, Brazil, to be 3-5 years. Among the plant adaptations to these environmental variables are the presence of belowground meristematic and storage organs (Rachid-Edwards 1956, Rawitscher 1948, Rizzini & Heringer 1961, 1962). We predicted that in response to frequent fire, annual drought, and nutrient-poor soils, a greater portion of plant biomass in the Cerrado would be belowground, such that root biomass and root:shoot ratios would be high relative to other tropical ecosystems. If true, a relatively minor percentage of the plant biomass is exposed to natural ecosystem disturbances (e.g., natural fires), whereas all of the plant biomass (and related C and nutrient pools) could be affected by human perturbations (e.g., land use/ land cover changes).

Given the areal extent of the Brazilian Cerrado, large scale anthropogenic perturbations could alter global source/sink dynamics of C and other greenhouse gasses. Klink et al. (1994) estimated that as of 1991, 600,000 km^2 of Cerrado had been cleared with an annual rate of 20,000 km^2 y^{-1}. This exceeds the deforestation rates of the tropical evergreen forests of the Amazon (e.g., 230,00-415,000 km^2; Fearnside 1992; Skole and

Tucker 1993). An accurate assessment of aboveground and belowground biomass of intact Cerrado vegetation types is a necessary step in determining the consequences of land conversion on local, regional and global processes. To address this research need, we established the following objectives: (1) quantify total aboveground biomass before and after fire in four plant communities forming a common vegetation gradient consisting of grassland, savanna and woodlands; and (2) quantify total belowground biomass (TBGB), root distribution and root structure along this same gradient.

STUDY SITE

Research was conducted during the latter part of the dry season and early part of the wet season, 1993, at the Reserva Ecológica do Instituto Brasileiro de Geografia e Estatística (IBGE) and the Jardim Botânico de Brasilia (JBB). These sites are located ≈ 35 km south of Brasilia, Brazil (15° 51' S 47° 63' W). The elevation is 1,100 m and slopes are < 10%. From 1980 to 1992, mean annual temperature varied from 19°C to 22°C. Mean precipitation was 1482 mm and distributed in two distinctive seasons; a wet season from October to March with a mean precipitation of 1257 mm and a dry season from April to September with a mean precipitation of 225 mm. Mean maximum relative humidity was 81% in December and the mean minimum was 55% in August (File data from Reserva Ecológica do IBGE 1980-1992).

The vegetation of the Brazilian Cerrado is characterized by five community types along a gradient of increasing woody species dominance: campo limpo (pure grassland), campo sujo (a savanna with a sparse presence of shrubs), campo cerrado (a dominance of shrubs with scattered trees and a grass understory), cerrado *sensu stricto* (a dominance of trees with scattered shrubs and a grass understory), and Cerradão (a closed canopy forest) (Coutinho 1978, Eiten 1972, Goodland & Pollard 1973). Within the common cerrado *sensu stricto*

community, stands with a more open tree canopy are referred to as cerrado aberto and those with a more closed canopy as cerrado denso. In this study, biomass and fires were measured in campo limpo, campo sujo and in the two variants of Cerrado *sensu stricto* (cerrado aberto and cerrado denso). Cerrado *sensu stricto* and campo sujo communities are usually found on Latosols (Oxisols) and Podzolic soils (Alfisols or Ultisols); campo limpo is associated with Lithosols (Lithic dystropepts) in the uplands and with hydromorphic soils (Inceptisols) in low areas ecotonal to riparian zones and other wet areas (Haridasan 1990). Soils in all sites have low nutrient concentrations, high aluminum contents, and low pH.

METHODS

Aboveground Biomass

Measurements of TAGB in this study includes all living vegetation (phytomass) as well as dead vegetation (necromass). TAGB was partitioned into components based on plant morphology and their variable influences and responses to fire. All prefire sampling of TAGB occurred within one week before burning and postfire TAGB was measured within one week after fire. In each of the four sampled communities, four clusters of 15 m transects were established. Downed wood debris was quantified along 6 transects in each cluster (n=24/community). Other components were measured in four transects in each cluster (n=16/community). The first cluster was randomly established and the others were systematically established 50 m in distance from each other. Aluminum stakes marked the end of each transect to ensure their exact relocation after fire.

Downed wood debris. Downed wood debris was quantified in cerrado aberto and cerrado denso using the planar intersect technique (Brown 1971, Brown & Roussopoulos 1974, Van Wagner 1968). This component was not present in the campo limpo and campo sujo grasslands. Dead wood was partitioned into diameter size classes based upon the following standard timelag classes: 0 to 0.64 cm in diameter (1-hr timelag fuels), 0.65 to 2.54 cm in diameter (10-hr timelag fuels), 2.55 to 7.6 cm in diameter (100-hr timelag fuels) (Deeming *et al.* 1977). No wood > 7.6 cm in diameter (≥1000-hr timelag fuels) was encountered in the plots. The timelag constant is the time period required for a wood fuel particle to lose 63 % of its initial moisture content when placed in an equilibrium temperature of 27° C and relative humidity of 20% (Pyne 1984). The 1-hr timelag fuels were measured along the first 5 m of the transect; 10-hr fuels were measured from 0 to 10 m, and the 100-hr fuels were measured along the entire 15 m transect. Biomass was calculated utilizing the formulas provided by Brown (1974) and adapted to the Cerrado by Kauffman *et al.* (1994). After fire, the transects were remeasured to quantify residual plant materials that were not consumed.

Herbaceous stratum, litter, and ash. The herbaceous stratum contained hardwood litter, green and dry graminoids, terrestrial members of the Bromeliaceae and Palmae, and small dicots (defined as those <1.0 cm in diameter and/or those with main stems ≥1.0 cm in diameter, but <0.50 m in height). All materials within a 25 x 25 cm microplot placed at the 5 and 10 m points along each transect were collected by clipping at the soil surface, and then oven-dried at 60 °C for 48 h to obtain dry-weight mass (n=32 plots/community). Samples from 10 microplots in each community were randomly selected for separation of the total

biomass into the components listed above. The ratio of each component to the total mass was calculated through this separation. This specific ratio for each community was utilized to calculate mass of each component in each community. Post-fire mass of this layer was collected along each transect at 6 and 11 m, employing the same methods as pre-fire sampling.

Ash mass was calculated through collection of all ash in a 50 x 50 cm plot placed at the 6 m point on each transect in each cluster (n=16). Ash was collected using a vacuum cleaner and electric generator.

Shrubs. All woody plants with a main stem ≥1.0 cm in diameter, and with a height range of 0.5-2.0 m were measured in a 1 x 5-m belt transect established adjacent to the transects. The height and elliptical crown area of all shrubs in each plot were measured. The elliptic crown area was calculated as the longest canopy diameter multiplied by the perpendicular diameter and π, and then divided by four. Crown volume was calculated by multiplying elliptic crown area by height. Biomass of shrubs was calculated through multiple regression analysis with volume, stem diameter and height as independent variables. This model was developed based upon destructive sampling of 20 shrubs collected at the Ecological Reserve. After fire, plots were remeasured utilizing the same methods.

Trees. The diameter and height of all trees (>2.0 m in height) were measured in 3 x 15-m plots established adjacent to the herbaceous and wood transects. Diameter measurements were taken at heights of 0.30 m and 1.30 m. These measurements were made because most studies in Cerrado refer to a basal area at 0.30 m (Felfili & Silva 1993, Ramos 1990, Sambuichi 1991, Silberbaur & Eiten 1987). However, equations used for the

calculation of tree biomass were based on the diameter at 1.30 m. Tree density was also calculated from the transects. Tree biomass was calculated using the equation presented by Brown *et al.* (1989) for moist tropical forests. Although this equation was not developed specifically for Cerrado trees, it is believed to be very robust and the most applicable (Dr. S. Brown, US-EPA Corvallis OR U.S.A., pers. comm.). This study provides a preliminary estimate of tree biomass even though the accuracy of this biomass model for Cerrado trees has not yet been determined.

Analysis of Variance (ANOVA) was utilized to test for differences in total biomass, the individual components of biomass, and fire consumption among plant communities. We found that means were correlated positively with the variance (i.e. greater means were followed by greater variance). Therefore, data were log-transformed prior to analysis (Sokal & Rohlf 1981). However, because results of the ANOVA with log-transformed data were not different from original data at a confidence level of 90%, they are presented here without the transformation. If significant differences in communities were found ($p \leq 0.10$), the protected least significant difference multiple range test was applied to determine the differences among communities.

Fire behaviour. Ambient temperature (°C), relative humidity (%), wind speed (m s^{-1}), wind direction, and cloud cover were measured at the time of ignition. Fires were ignited as perimeter or circle fires except for the campo limpo site which was ignited with a backfire pattern (against the wind), due to high wind speeds at the time of ignition.

Observations of flame characteristics and fire behaviour were recorded at 3-10 random locations during each fire. Measurements included flame length, flame height, flame depth, and flame angle (Alexander 1982). In addition, the rate of spread (m min^{-1}), and residence time (s) were recorded (Rothermel and Deeming 1980, Alexander 1982). With these data, fireline intensity (kW m^{-1}), reaction intensity (kW m^{-1}), and heat per unit area (kJ m^2) were calculated according to formulas reported in Rothermel and Deeming (1980) and Alexander (1982).

Moisture content. At each site, at the time of ignition, moisture contents of graminoids, litter, herbaceous dicots, wood debris and soils were determined on a dry weight basis. A few minutes prior to ignition, 5 samples of each component were placed in air-tight soil containers and weighed in the field to determine fresh weight. In the laboratory, they were dried at 100°C for 24 h and then reweighed.

Belowground Biomass

Root biomass was quantified by a combination of monolith and auger methods (Böhn 1979). Five monoliths 50 cm x 50 cm in area were sampled in each community type. The first sample was randomly selected within the stand and the others were systematically selected along a transect ≈20 m in distance from each other. Prior to excavation, all aboveground vegetation was cut and removed and a trench was dug immediately adjacent to the area to be sampled. Roots and soil within the monolith were excavated and separated into layers (0-10 cm, 10-20 cm, 20-30 cm, 30-50 cm and 50-100 cm). From the 100 cm to 200 cm depth a 15

cm diam. core was extracted with an augur and was completely sampled to determined root mass of this layer.

All materials (soil and roots) were sieved in the field. Roots were taken to the laboratory, and dried at 60 °C for 48 h and weighed. Later, roots were separated into five classes according to diameter: ≤ 5 mm, 6-10 mm, 11-20 mm, 21-30 mm, and "tubers". The "tuber" category includes all other belowground structures found in the Cerrado, such as tubercle roots, xylopodia, lignotubers and rhizomes. A non-parametric Kruskal-Wallis test was applied to test for differences among root biomass of communities (p-value$\geq$0.10). If significant, a Mann-Whitney test was applied to determine where differences among the communities existed (Sokal & Rohlf 1981).

RESULTS

Pre-fire Aboveground biomass

Along the gradient from campo limpo to cerrado denso, TAGB ranged from 5.5 to 24.9 Mg ha^{-1} (Table 1). The TAGB was significantly different between the campo limpo, campo sujo, and the woodland communities (cerrado aberto and cerrado denso). Total graminoid biomass (live and dry grasses combined) was significantly greater in the campo limpo and campo sujo than in the cerrado aberto and cerrado denso. Aboveground biomass of graminoids in campo limpo accounted for 72 % of the TAGB, while in campo sujo, it accounted for 45 %. In contrast, graminoids accounted for 8% and 7% of the TAGB in cerrado aberto and cerrado denso communities, respectively. Cerrado aberto and cerrado denso had significantly greater litter biomass than campo limpo and campo sujo. Biomass of small dicots, palms and bromeliads was significantly higher for cerrado aberto than for other

communities (Table 1). Total dead wood debris comprised 7 % of TAGB of cerrado aberto and cerrado denso and the distribution of the mass among size classes was similar in these two communities.

Among the three communities with a shrub (arvoreta) component, density was significantly higher in cerrado aberto (1347 ha^{-1}) than campo sujo and cerrado denso (650 and 844 ha^{-1}, respectively; Table 2A). Average basal area and height of shrubs was greatest in cerrado aberto. This was reflected in its significantly higher shrub biomass compared to other communities (Table 1).

The tree component was the most apparent structural difference among the communities (Table 2B). Tree density ranged from 0 and 28 ha^{-1} in the campo limpo and campo sujo communities to >1000 ha^{-1} in the cerrado denso community. Mean and maximum tree height increased along this vegetation gradient. In addition, both the mean tree size (basal area) and the total basal area of the community significantly increased along the gradient from grasslands to cerrado denso. Tree biomass was significantly higher for cerrado denso than for cerrado aberto and campo sujo (Table 1). Trees comprised $\leq$1% of the TAGB in campo limpo and campo sujo, but 27 and 52% in cerrado aberto and denso, respectively.

The fuel load is defined as the portion of aboveground biomass that is susceptible to fire consumption (e.g., biomass of downed wood debris, litter, herbaceous materials and shrub leaves; Kauffman *et al.* 1994). In campo limpo this was equivalent to the TAGB. The fuel load significantly increased from campo limpo to cerrado aberto, but decreased in the tree-dominated cerrado denso (Table 1).

Fuel conditions and fire behaviour

The campo sujo, cerrado aberto, and cerrado denso communities were burned in August, 1993 prior to the onset of the rainy season compared to the campo limpo which was burned in October, 1993 following the onset of the rainy season. Weather conditions were similar at the time of burning for all communities, except for campo limpo, which had higher wind speeds (5-6 km h^{-1}). Ambient temperatures ranged from 27° C to 32° C, and relative humidity averaged 36 % (Table 3). Differences in the season in which campo limpo was burned were strongly reflected in the mean moisture content of graminoids which is the dominant component responsible for sustained ignition and spread. Graminoid moisture content was very high in campo limpo (53%), while it was about half that in the woodland communities (24-27%) and quite low in campo sujo (9%). In cerrado aberto and cerrado denso, wood debris and litter had the lowest fuel moisture of all sampled components; moisture content of these components were ≤6% (Table 3).

The influence of differences in community structure, fuel moisture conditions at the time of burning, and patterns of ignition were likely reflected in differences observed in fire behaviour of the plant communities. Flame length ranged from 1.4 m in campo limpo to 3.4 m in cerrado denso. Rate of fire spread was much slower in the campo limpo with comparatively moist fuels and with a backing fire spreading against the wind contrasted to that of the cerrado aberto and denso with drier fuels with a perimeter fire. In general, all measures of fire intensity increased along the gradient from campo limpo to cerrado denso (Table 4). For example, fireline intensity increased from 557 to 3,693 kW m^{-1} while reaction intensity increased from 506 to 1,319 kW m^{2}.

Biomass consumption by fire

The percentages of TAGB consumed by fire (the combustion factor) were 92% and 84% for campo limpo and campo sujo, respectively. The combustion factors for cerrado aberto and denso were significantly lower at 54% and 33%, respectively. In both campo limpo and campo sujo, only minute amounts of green grass and dicots remained after burning. The combustion factor of dry graminoids and litter components for all communities was ≈100%. Higher consumption rates were measured for smaller compared to the larger diameter classes of wood debris. Total shrub biomass consumption (stem and leaves combined) was greatest in cerrado aberto (35%). However, shrub leaves had a combustion factor ranging from 83% in cerrado denso to 99% in campo sujo. Neither the mainstems nor the leaves of trees were consumed by fire. The consumption of the fuel load was high for all communities (87-97 %), and differences were not detected among communities (Table 1). The quantity of biomass consumed by fire increased across the gradient from 5.1 Mg ha^{-1} in campo limpo, to 13.4 Mg ha^{-1} in cerrado aberto, but in cerrado denso, consumption declined to 8.0 Mg ha^{-1}.

Post-fire aboveground biomass

Post-fire biomass reflected the prefire composition of the communities and their inherent susceptibility to consumption by fire. The post-fire TAGB significantly increased from campo limpo (0.4 Mg ha^{-1}), to campo sujo (1.4 Mg ha^{-1}), to the woodland communities (11.4 and 17.0 Mg ha^{-1} for cerrado aberto and cerrado denso; Table 1). Shrub stems and the relatively intact trees comprised the dominant aboveground biomass components in cerrado aberto and cerrado denso after fire.

Other than trees, charred shrub stems, and ash, little else remained aboveground following fire. Ash mass was greatest in cerrado aberto and cerrado denso, and was lowest in campo limpo (Table 1).

Belowground biomass

TBGB in all communities was quite high relative to the quantity of aboveground biomass and followed a similar pattern of increasing biomass along the vegetation gradient from campo limpo to cerrado denso. TBGB in campo limpo (16.3 Mg ha^{-1}) and campo sujo (30.1 Mg ha^{-1}) were significantly different from cerrado aberto (46.6 Mg ha^{-1}) and cerrado denso (52.9 Mg ha^{-1}; Figure 1).

Root biomass was concentrated in the upper layers of the soil horizon in all communities (Figure 1). The decrease in root abundance with increasing soil depth was most dramatic in campo limpo, the community without woody vegetation. Roots in the top 10 cm comprised approximately 50% of the TBGB in campo limpo, campo sujo, and cerrado aberto, but only 31% in cerrado denso. Root biomass and the proportion of the TBGB present in the 10-20 cm soil layer increased from campo limpo (10 %) to cerrado denso (31%). In all communities >80 % of the TBGB was present in the upper 30 cm of the soil profile except in cerrado denso (where 71% was found in the upper 30 cm of soil). Roots present at the 30-50 cm soil depth comprised 5 to 12% of the TBGB. At depths of 50-100 cm, roots comprised 5 to 13% of the total pool. Only 3 to 4% of the TBGB occurred at a depth of 100-200 cm except in campo limpo.

Of all size classes, fine roots ≤ 5 mm in diameter comprised the greatest proportion of total root biomass in all communities (Figure 2). While the biomass of fine roots increased

along the Cerrado vegetation gradient from campo limpo to cerrado denso, their relative contribution decreased. The relative abundance of fine roots in campo limpo, campo sujo, cerrado aberto and cerrado denso was 56%, 46%, 40% and 29%, respectively. Coarse root biomass (diameter classes ≥ 6 mm) increased by over 5-fold along the vegetation gradient: 7.1 Mg ha^{-1} (comprising 44% of the TBGB) in campo limpo; 16.3 Mg ha^{-1} (54% of the TBGB) in campo sujo; 28.0 Mg ha^{-1} (60% of the TBGB) in cerrado aberto; and 37.5 Mg ha^{-1} (71% of the TBGB) in cerrado denso (Figure 2). Tubers were present in all communities ranging from 9% of the TBGB in campo sujo to 23% in cerrado aberto.

Combining aboveground biomass data from the same sites (Table 1) with the belowground data provides a clear description of increasing structure and phytomass along this vegetation gradient. Total ecosystem phytomass (live aboveground biomass and root biomass) along the Cerrado gradient was: 19.2 Mg ha^{-1} in campo limpo, 34.1 Mg ha^{-1} in campo sujo, 64.2 Mg ha^{-1} in cerrado aberto and 73.3 Mg ha^{-1} in cerrado denso. Root:shoot ratios were higher in the grass dominated communities compared to the woodlands (Table 1). The root:shoot ratio ranged from 7.7 in campo sujo to 2.6 in cerrado aberto. Total ecosystem biomass (aboveground live and dead biomass + TBGB) ranged from 21.9 Mg ha^{-1} in campo limpo to 77.9 Mg ha^{-1} in cerrado denso. Belowground plant tissues comprised 65-76% of this total ecosystem biomass. In terms of the total ecosystem biomass, fires consumed ~23% of that in campo limpo, 20% in campo sujo, 19% in cerrado aberto, and 10% in cerrado denso.

DISCUSSION

Pre-fire aboveground biomass

The TAGB for cerrado denso (24.9 Mg ha^{-1}) was low compared to other common Brazilian tropical ecosystems (i.e., dry and evergreen forests) For example, Kauffman *et al.* (1993) reported that the mean TAGB of Caatinga, a Brazilian tropical dry forest, was 74 Mg ha^{-1}. The TAGB of evergreen forests in the Amazon states of Para and Rondonia ranged from 290 to 435 Mg ha^{-1} (Kauffman *et al.* 1995). The TAGB of the cerrado denso community in this study was <9% of the tropical evergreen forests.

The Brazilian Cerrado is not a uniform savanna ecosystem but is comprised of a mosaic of vegetation communities, each with a unique composition and structure (Eiten 1972). This is exemplified by the 5-fold increase in TAGB along the gradient from campo limpo to cerrado denso. Along a similar vegetation gradient at the IBGE Ecological Reserve, Kauffman *et al.* (1994) reported a fuel load of 7.1 Mg ha^{-1} for campo limpo, 7.3 Mg ha^{-1} for campo sujo, 8.6 Mg ha^{-1} for campo cerrado, and 10.0 Mg ha^{-1} for cerrado *sensu stricto* (trees were not measured in this study). Our measurements of the biomass of campo sujo are similar, while those of campo limpo are lower (Table 1). In this study, the fuel load of cerrado aberto and cerrado denso was slightly higher than the fuel loads of campo cerrado and cerrado *sensu stricto* reported by Kauffman *et al.* (1994). These differences exemplify both annual and site variability for communities of this ecosystem. Given the large area covered by the Brazilian Cerrado (1.8 million km^2) with great climatic and soil variability, caution should be made in using these biomass data as representative for all of the Brazilian Cerrado.

Based upon fuel wood inventories, Fearnside (1992) estimated the TAGB of Cerrado ranged from 11 to 52 Mg ha^{-1}. The biomass of the cerrado denso and aberto fall within the range proposed by Fearnside (1992), while the grassland types are much lower. Pivello & Coutinho (1992) found that the biomass of the surface layer of a campo cerrado community

ranged from 4.9-7.7 Mg ha^{-1} (trees and shrubs were not measured). This is similar to the surface layers of communities measured in this study.

Fire behaviour

Fire has both short and long-term influences on Cerrado ecosystem structure and function. The immediate influences on structure and function include consumption of aboveground biomass, nutrient loss, and transformation into ash (Kauffman *et al.* 1994, Pivello & Coutinho 1992). Variation in structure influence both the flammability and fire behaviour that occur within the communities. In addition, the influence of fire on vegetation composition and structure is a function of the fuel consumption and fire intensity which are influenced by weather conditions at the time of burning, topography, and fuel moisture content (Chandler *et al.* 1983, Pyne 1984). Weather conditions were similar for campo sujo, cerrado aberto, and cerrado denso which were conducted within 13 days of one another. Therefore, differences in fire behaviour for these communities are probably due to differences in the fuel structure, arrangement, moisture content, and the total quantity of biomass consumed.

Under low moisture conditions and when the distribution of grasses and/or grass litter is continuous, fires in grasslands potentially have the most rapid rate of spread of all natural communities (Brown & Davis 1973, Chandler *et al.* 1983). Campo sujo was burned at the end of the dry season when the graminoid component had a very low moisture content (9%). Compared to campo limpo, this likely contributed to the higher fireline intensity and rapid spread of fire; an area of 10 ha burned in less than 11 min. We predicted that given similar weather conditions at the time of burning, fire behaviour in campo limpo would have been equally or more dramatic than campo sujo. However, because campo limpo was burned after a series of successive rains, grass moisture content was much higher. In addition, it was

necessary to use a backfire ignition pattern in campo limpo because of high wind speeds. These factors likely lowered flame lengths and rate of spread in this community.

Belowground biomass

The significant differences in TBGB tended to parallel the obvious aboveground differences in community structure along the Cerrado gradient. As aboveground biomass and woody dominance increased, biomass and structural heterogeneity of the TBGB also increased. In ecosystems such as tropical savannas with frequent fire-return intervals, the partitioning of a greater proportion of biomass belowground has been suggested to be an adaptation facilitating persistence in such a disturbance regime (Gill 1981). Environmental factors affecting root structure and biomass also include characteristics such as moisture dynamics, macronutrient availability, soil depth, and other physical characteristics (Richards 1986, Rizzini & Heringer 1961). Goodland & Pollard (1973) studied the relationship of soil chemistry and vegetation structure along a Cerrado vegetation gradient from campo sujo to Cerradão. They found higher soil nutrient concentrations in those community types with a greater tree density and basal area. Given the close proximity of the sampled sites in this study, differences in TBGB and the root structure and distribution between communities are likely the biotic reflections of site differences in chemical, physical, and moisture conditions of the soil as well as the influences of fire (Kauffman *et al.* 1994).

This is the first study to quantify the TBGB to a 2 m depth in the Brazilian Cerrado. Compared with other tropical savannas and woodlands, the range of TBGB (16.3 Mg ha^{-1} to 52.9 Mg $ha^{-1)}$ for the Cerrado was quite high. Along a vegetation gradient from grassland to woodland in the Venezuelan llanos, root biomass ranged from 11.4 to 18.9 Mg ha^{-1} (Sarmiento & Vera 1979). Along a gradient from grassland to woodland in Lamto savanna,

Ivory Coast, Africa, herbaceous root biomass decreased from 19.0 Mg ha^{-1} to 10.1 Mg ha^{-1} while woody species root biomass increased from 0 to 26.0 Mg ha^{-1} (Menaut & Cesar 1979).

Although total root biomass in the Cerrado was higher than in other comparable savannas, root distribution by depth was similar. The root biomass of Venezuelan and Ivory Coast savannas also were concentrated in the surface soil layers (Menaut & Cesar 1979, Sarmiento & Vera 1979). In campo limpo, the significant decrease in root biomass below 10 cm reflects the distinctive root system displayed by graminoids which comprised 71% of the total aboveground biomass of this community. In campo sujo, cerrado aberto, and cerrado denso, root biomass declined in a more gradual manner with increasing soil depth; there was no significant difference in root biomass between the 0-10 and 10-20 cm soil depths for cerrado aberto and cerrado denso (Figure 1). This likely reflects the increasing dominance of shrubs and trees that exploit deeper areas of the soil profile. In cerrado denso, the greater abundance of roots in the 30 to 100 cm depth suggests a greater exploitation of deeper soil layers. Lawson *et al.* (1968) reported a similar stratification of roots in Guinea savanna with a greater quantity of large diameter roots of shrub and trees at depths of 20-30 cm overlain by the majority of grass roots in surface layers.

At the IBGE Reserva Ecológica, 1,100 plant species in 135 families have been identified (file data from the IBGE Reserva Ecológica herbarium). The great plant species diversity in the Cerrado implies an interspecific coexistence of species of variable root architectures, which facilitates efficient exploitation of water and nutrients at different depths. Nevertheless, the greatest proportion of the root biomass (62-79%) were concentrated in the top 20 cm of the soil horizon (Figure 1). This was similar to Lamto Savanna in Africa where 80 % of the root biomass also occurred in surface soils (Menaut & Cesar 1979). While only a

small proportion of roots (3-4%) were found at depths of 1-2m, roots have been reported to penetrate as deep as 19 m in the Brazilian Cerrado (Rawitscher 1948). The ecological significance of these deep roots in terms of water and nutrient uptake is in need of further exploration.

Large roots, tubers and other belowground structures occurred in all communities but were found in the greatest abundance in the cerrado aberto and denso communities. They are organs of water, nutrient and energy storage that facilitate survival during the dry season (Rizzini & Heringer 1961). These belowground organs often possess dormant meristematic tissues that facilitate regeneration following fires. Vegetative regeneration from belowground tissues is far more common than sexual reproduction in most grasses, trees, and shrubs of the Brazilian Cerrado (Rizzini 1976). These are important adaptations for persistence in an environment where frequent surface fires may kill aerial plant organs but soil heat flux is minimal (Kauffman 1990). Miranda *et al.* (1993) found that during Cerrado fires aboveground temperature maxima of the flame front ranged from 85°C to 840°C. In contrast, soil was a very effective thermal barrier; negligible temperature increases were recorded below a 5 cm soil depth. When aboveground tissues are destroyed by fire, shoots arise from belowground meristematic tissues even prior to the onset of rain (Rizzini & Heringer 1961). Although trees in the Brazilian Cerrado are well adapted to fire, in the days following the burns it was observed that leaves in some tree canopies as high as 5 m in height died due to lethal scorch temperatures. We also observed that replacement of leaf area in trees and shrubs occurred within a month after loss even prior to the onset of the rainy season.

The four communities of the Brazilian Cerrado measured in this study had a very high root:shoot ratio compared to tropical deciduous and evergreen forest ecosystems (Table

4). In addition to adaptations of frequent surface fires, evergreen plants in the Cerrado persist in an environment with a pronounced dry season of 3-5 months. However, tropical dry-deciduous forests also occur in environments with long dry seasons (Brown & Lugo 1992, Castellanos *et al.* 1991 Murphy & Lugo 1986), but without a history of frequent surface fires. Compared to dry forest, the root:shoot ratios in our sampled Cerrado communities were three times higher. This high root:shoot ratio may reflect plant adaptations to the occurrence of frequent surface fires which are common in the Brazilian Cerrado, but infrequent in deciduous and evergreen forests.

This study quantified the biomass, structure and fire consumption of plant communities along a common vegetation gradient from grassland to dense woodland in the Brazilian Cerrado. The quantity of mass, arrangement, vegetation composition, and resultant emissions are quite different in fires of the Cerrado compared to other Brazilian tropical ecosystems (Ward *et al.* 1992). Consumption of biomass in slash fires in the Caatinga, a tropical dry forest in Northeastern Brazil ranged from 57 to 70 Mg ha^{-1} (Kauffman *et al.* 1993). In slashed primary Amazon evergreen forest, the biomass consumption in slash fires ranged from 125 to 227 Mg ha^{-1} (Kauffman *et al.* 1995). However, this is a comparison of fires burning natural savannas to anthropogenic fires in slashed forests. On an equivalent areal basis, the release of CO_2 as well as other emissions to the atmosphere would be dramatically lower in Cerrado fires than slash fires in tropical forest ecosystems. Moreover, because of well-adapted morphological and reproductive traits, Cerrado vegetation recovers rapidly after fire resulting in C uptake to pre-fire levels in one to two years.

The increase in belowground biomass from campo limpo to *cerrado* denso paralleled the increase of aboveground biomass along this vegetation gradient. In the Brazilian

Cerrado, a remarkable proportion of the phytomass is partitioned belowground. While TAGB of cerrado denso is much less than that of tropical dry and evergreen forests, the total belowground biomass was similar or even greater (Table 5). Because of the large belowground biomass, the Brazilian Cerrado may be a more significant global C pool than previously thought. While natural fires may not result in significant disruptions in the C balance of the Cerrado ecosystem, deforestation, slash burning, and replacement by a crop monoculture may shift the functional role of trees and belowground pools from C sinks to atmospheric sources. In addition to altering the C budget through slash burnng and belowground C depletion, large-scale crop conversions would also result in great losses of plant diversity thereby diminishing the potential for ecosystem recovery or restoration.

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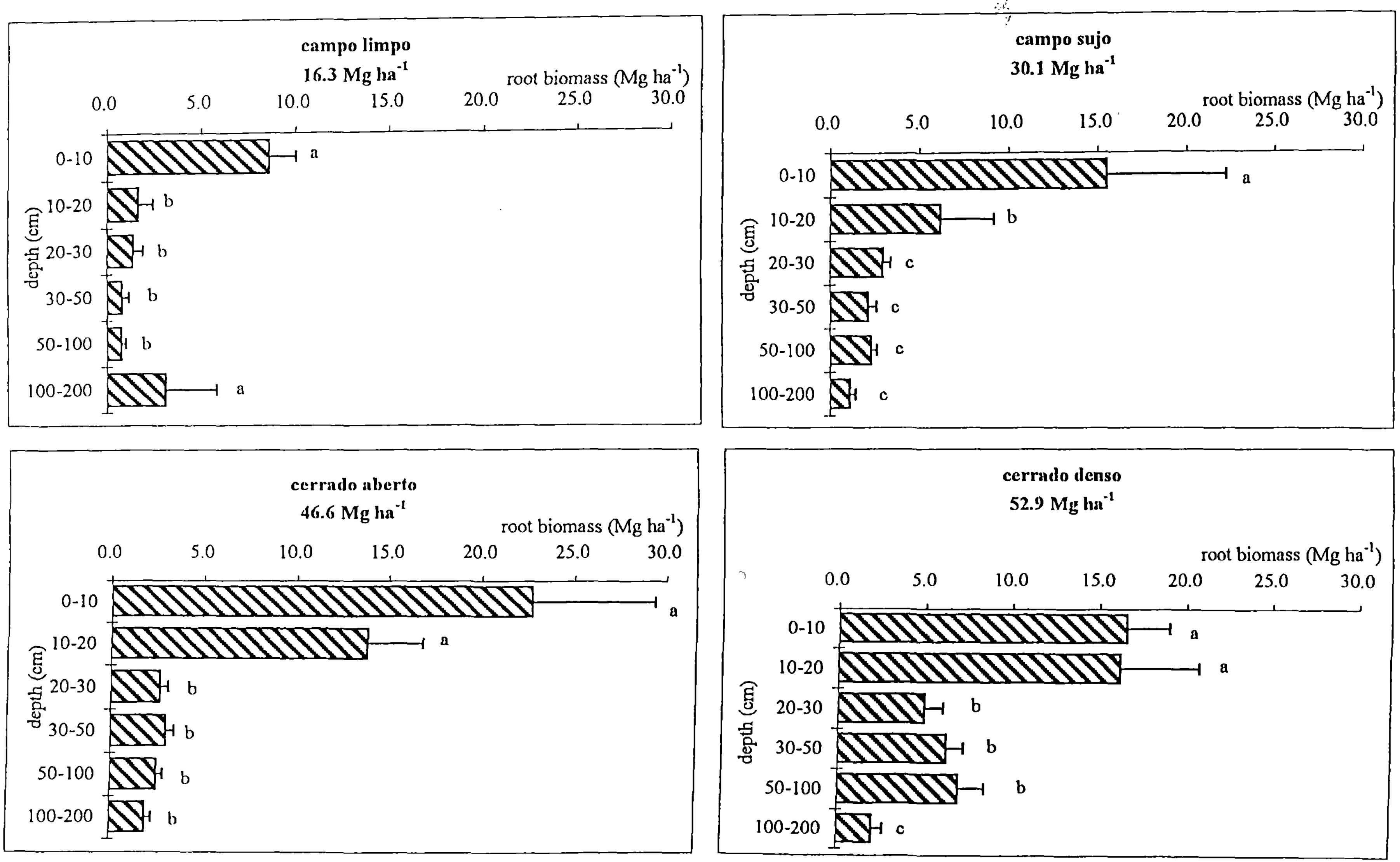

Figure 1. Root biomass distribution by depth along a Cerrado vegetation gradient near Brasilia, Brazil. Different letters refer to significant differences in biomass by depth within each community (p-value <0.10).

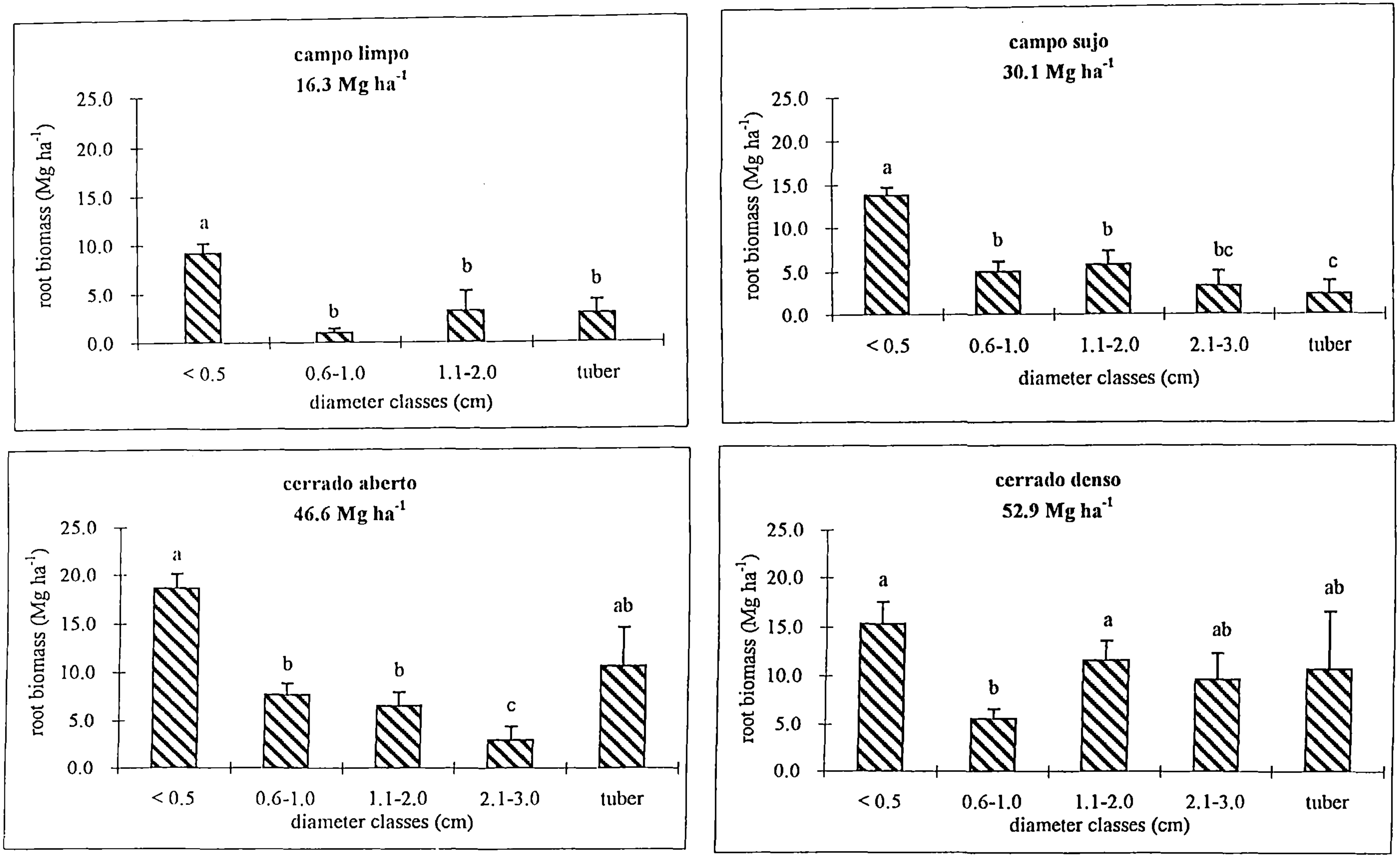

Figure 2. Belowground biomass partitioned by diameter along a Cerrado vegetation gradient, near Brasilia, Brazil. In campo limpo, roots with a diameter between 2.1-3.0 cm were absent. Different letters refer to a significant differences in biomass between diameter and tuber classes within each community (p-value≤ 0.10).

Table 1. Total aboveground biomass (Mg ha^{-1}) before, after fire, and the combustion factor (%) along a vegetation gradient in Cerrado near Brasilia, DF, Brazil (August-October, 1993). Numbers are mean ± standard error.

	Campo limpo			Campo sujo			Cerrado aberto			Cerrado denso		
component	pre fire	post fire	C. factor	pre fire	post fire	C. factor	pre fire	post fire	C. factor	pre fire	post fire	C. factor
HERB LAYER												
litter	0.6 ±0.1 a	0.0	100 ±0	1.9 ±0.3 b	0.0	100 ±0	3.8 ±0.3 c	0.0 ±0.0	100 ±0	3.3 ±0.2 c	0.0 ±0.0	100 ±0
dry graminoids	2.0 ±0.1 a	0.0	100 ±0	3.4 ±0.3 b	0.0	100 ±0	1.7 ±0.2 ac	0.0	100 ±0	1.4 ±0.1 c	0.0 ±0.0	100 ±0
green graminoids	1.9 ±0.0 a	0.2 ±0.0 A	90 ±2 A	7.8 ±0.1 b	0.1 ±0.0 B	90 ±4 A	0.3 ±0.0 c	0.0 ±0.0 B	95 ±1 A	0.3 ±0.0 c	0.0 ±0.0 B	91 ±2 A
total graminoids	4.0 ±0.3 a	0.2 ±0.0 A	96 ±1 A	4.2 ±0.4 a	0.1 ±0.0 B	99 ±0 B	2.0 ±0.2 b	0.0 ±0.0 B	99 ±0 B	1.7 ±0.1 b	0.0 ±0.0 B	98 ±0 B
dicot, palm and bromelia	1.0 ±0.1 a	0.3 ±0.2 A	96 ±1 A	1.4 ±0.2 a	0.1 ±0.0 A	89 ±3 A	4.5 ±1.3 b	0.3 ±0.1 B	90 ±4 A	2.0 ±0.2 a	0.3 ±0.1 A	90 ±3 A
WOOD DEBRIS												
0-0.64 cm	-	-	-	-	-	-	0.3 ±0.1	0.0 ±0.0	89 ±3 A	0.3 ±0.0	0.1 ±0.0	79 ±4 B
0.65-2.54 cm	-	-	-	-	-	-	0.6 ±0.1	0.2 ±0.0	62 ±8	0.6 ±0.1	0.2 ±0.0	53 ±8
>2.54 cm	-	-	-	-	-	-	0.8 ±0.1	0.4 ±0.1	42 ±10	1.0 ±0.2	0.5 ±0.2	39 ±10
total	-	-	-	-	-	-	1.7 ±0.2	0.6 ±0.1	67 ±6	1.9 ±0.2	0.8 ±0.2	55 ±6
SURFACE LAYER												
herb layer+woody debris	6 ±0 a	0.4 ±0.2 A	92 ±5 A	7.5 ±0.5 ab	0.2 ±0.0 B	97 ±1 A	12.1 ±2.0 b	0.9 ±0.2 AB	92 ±3 B	8.8 ±0.8 ab	1.1 ±0.2 B	87 ±21 A
SHURB												
leaf biomass	-	-	-	0.2 ±0.1 a	0.0 ±0.0	99 ±2 A	0.7 ±0.1 b	0.1 ±0.0	89 ±4 B	0.4 ±0.1 c	0.1 ±0.0	83 ±6 B
total biomass	-	-	-	1.7 ±0.3 a	1.1 ±0.2 A	27 ±6 A	6.2 ±0.5 b	3.9 ±0.4 B	35 ±5 A	3.2 ±0.5 c	2.9 ±0.4 B	10 ±1 B
FUEL LOAD	5.5 ±0 a	0.4 ±0.2 A	92 ±5	7.8 ±0.7 b	0.2 ±0.0 A	97 ±3	12.9 ±0.9 c	1.0 ±1.0 B	92 ±2	9.2 ±0.1 b	1.2 ±0.2 B	87 ±2
TREE	-	-	-	0.0 ±0.0 a	0.1 ±0.1 A	0	6.6 ±1.7 b	6.6 ±1.7 B	0	12.9 ±2.5 c	12.9 ±2.5 C	0
TOTAL(TAGB)												
surf layer+shrub+tree	5.5 ±0.3 a	0.4 ±0.2 A	92 ±5 A	9.3 ±0.8 b	1.4 ±0.1 B	84 ±1 B	24.8 ±2.5 c	11.4 ±1.2 C	54 ±4 C	24.9 ±2.9 c	17.0 ±2.6 C	33 ±3 C
ASH		0.4 ±0.0 A			1.3 ±0.9 B			2.2 ±0.3 C			1.5 ±0.2 B	

Different lower case letters denote a significant difference ($p \leq 0.10$) in biomass between communities before fire. Different upper case letters denote differences in biomass between communities after fire ($p \leq 0.10$). Different underlined uppercase letters denote a significant difference in combustion factors ($p \leq 0.10$) between communities. The absence of letters indicate no differences were found between communities. A dash ("-") denotes that components were not found in the community.

Table 2. Shrub (a) and tree (b) density, height and basal area of three community types along a vegetation gradient in Cerrado near Brasilia, DF. Numbers are mean ± standard error.

(a)

	Campo sujo	Cerrado aberto	Cerrado denso
SHRUBS			
Density (shrubs ha^{-1})	650±80 [a]	1347±110 [b]	844±97 [c]
Height (m)			
mean	0.81±0.34	1.05±0.04	0.93±0.05
range	0.13 - 1.43	0.50 - 1.94	0.55 - 1.77
*Basal area per shrub (cm^2 per shrub)	66.4±14.4	82.6±8.70	74.7±19.1
Basal area/ha ($m^2 ha^{-1}$)	4.3±0.9 [a]	11.1±1.6 [b]	6.0±1.3 [c]

(b)

	Campo sujo	Cerrado aberto	Cerrado denso
TREES			
Density (trees ha^{-1})	28±28 [a]	1069±124 [b]	1000±109 [b]
Height (m)			
mean	2.5±2.5 [a]	2.92±0.11 [b]	3.09±0.35 [b]
range	2.4-2.5	2.01-6.00	2.01-10.00
*Basal area per tree (cm^2 per tree)	0.0±0.0 [a]	80.2±12.5 [b]	145±16.9 [c]
Basal area/ha ($m^2 ha^{-1}$)	0.0±0.0 [a]	8.5±2.1 [b]	14.5±2.5 [c]

Different letters denote a significant difference ($p \leq 0.10$) among communities for both tables. The absence of letters indicate that no differences were found.

*Basal area was measured at the ground-level (0 cm) for shrubs and at 30 cm for trees.

Table 3. Weather conditions and fuel moisture content (%) at the time of prescribed burning along a vegetation gradient of Cerrado, near Brasilia, DF, Brazil. Data for fuel moisture content are means ± standard error.

	Campo limpo	Campo sujo	Cerrado aberto	Cerrado denso
DATE OF BURNING	7 October 1993	17 August 1993	30 August 1993	31 August 1993
WEATHER CONDITIONS				
Temperature (^{o}C)	27	27	32	30
Relative humidity (%)	40	37	35	31
Wind speed (km/h)	5-6	N/A	0-5	0-3
Wind direction	S-N	S-W	N	N
General conditions	cloudy	clear	-	hazy, partly cloudy
FUEL MOISTURE CONTENT (% dry weight basis)				
graminoids	53 ± 3	9 ± 1	27 ± 7	24 ± 5
dicot	114 ± 12	113 ± 8	111 ± 4	137 ± 5
woody debris	-	-	5 ± 1	6 ± 1
litter	-	-	5 ± 0	5 ± 1
soil	33 ± 1	33 ± 1	20 ± 2	18 ± 1

Table 4. Fire behavior along a vegetation gradient in Cerrado, near Brasilia, DF, Brazil. Data are means ± standard error.

	Campo limpo	Campo sujo	Cerrado aberto	Cerrado denso
Flame length (m)	1.4±0.2	2.8±0.5	3.1+0.4	3.4±0.3
Flame height (m)	1.2±0.2	2.2±0.5	2.7±0.3	2.9±0.4
Flame depth (m)	1.1±0.3	3.0±2.0	3.8±0.4	2.8±0.3
Flame angle (degree)	53±7	45±0	63±4	61±6
Rate of spread(m min^{-1})	2.0±1.0	no data	13.8±2.4	13.8±0.3
Residence time (s)	no data	no data	31.6±1.8	28.5±6.8
Fire line intensity (kW m^{-1})	557	2437	3094	3693
Reaction intensiy (kW m^{-2})	506	812	814	1319
Heat per unit area (kJ m^{-2})	278	no data	224	267

Table 5. Tree density (numbers ha^{-1}), shoot biomass ($Mg\ ha^{-1}$), root biomass ($Mg\ ha^{-1}$), and the root:shoot ratio (r:s) for common tropical ecosystems.

ecosystem	tree density	shoot	root	r:s	source
Tropical Savanna					
Cerrado (Brazil)					
campo limpo	-	2.9	16.3	5.6	this study (1)
campo sujo	12	3.9	30.1	7.7	this study
cerrado aberto	1064	17.6	46.6	2.6	this study
cerrado denso	1000	18.4	53.0	2.9	this study
Llano (Venezuela)					
grassland	-	6.0	11.5	1.9	Sarmiento & Vera 1979 (2)
woody savanna	100	5.3	19.0	3.6	Sarmiento & Vera 1979 (2)
Ivory Coast (Africa)					
grass savanna	-	3.5	19.0	5.4	Menaut & Cesar 1979 (3)
savanna woodland	800	61.3	37.1	0.6	Menaut & Cesar 1979 (3)
Tropical rain forest					
Brazil	10406	264.0	35.4	0.1	Nepstad 1989 (4)
Venezuela	no data	335.0	56.0	0.2	Jordan & Uhl 1978; Stark & Spratt 1977 (5)
Ghana	5300	233.0	54.0	0.2	Greeland & Kowal 1960 (6)
Tropical dry forest					
Puerto Rico	12000	53.2	45.0	0.8	Murphy & Lugo 1986 (7)
Mexico	4700	73.6	31.0	0.4	Castellanos *et al.* 1991 (8)

(1)- Aboveground biomass includes green grass, herbs, dicots, palms, bromeliads, shrubs and trees. Roots were measured up to 2.00 m in depth.
(2)- Root biomass was investigated up to 2.00 m in depth.
(3)- Roots were investigated to1.0 m in depth. Data are the sum of herbaceous and woody roots that were presented separately in the manuscript.
(4)- Aboveground biomass includes live trees $\geq$ 1.0 cm in diameter, and root biomass was measured up to 10.0 m in depth.
(5) and (6)- Root biomass was measured up to 0.50 m and 0.90 m in depth, respectively..
(7)- Aboveground biomass includes all live vegetation > 1.50 m in height, standing dead material and epiphytes.
(8)- Aboveground biomass included trees, shrubs and lianas. Roots were measured to 0.80 m in depth.

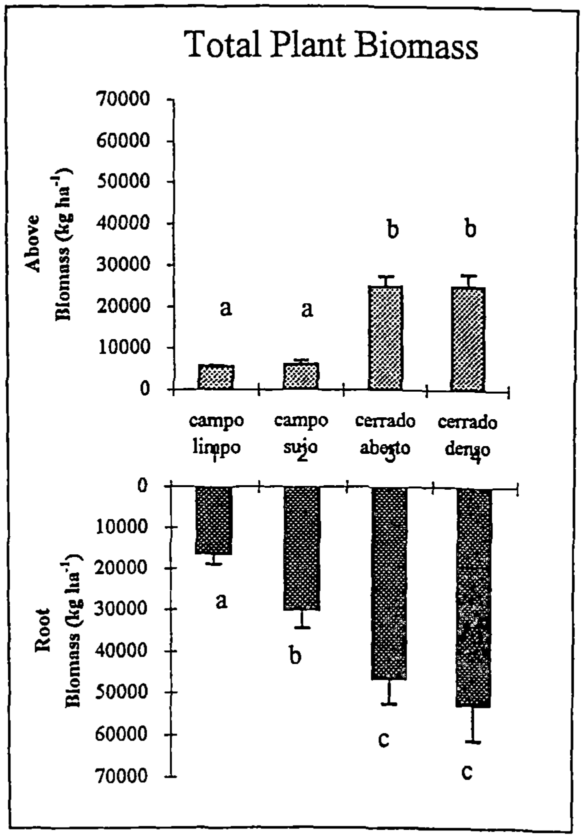

Figure 1. Comparison of aboveground and root biomass of Cerrado vegetation. Bars are standard errors. Different letters denote significant differences (p-value ≤ 0.10) when testing among communities using LSD test for aboveground biomass (N=4), and Mann-Whitney test (N=5) for root biomass.

V. PUBLICATIONS

We could find no relationship between the RADAMBRASIL forest inventory and the actual measurements of biomass that we conducted in the field. We Compared our actual field measurements with that of two prominently used models that estimate biomass from forest inventory. Neither was very accurate in their estimations. Yet much of this stems from the fact that we did not find the same volume as what was originally reported in the RADAMBRASIL volumes. This indicates that we could not replicate the RADAMBRASIL data set, thereby questioning its accuracy, or value in estimating biomass. Forest models can not take into account the variation in terms of belowground biomass, palm biomass, vine biomass, and other factors not related to large trees (i.e., those >30cm dbh).

In the last chapter we present the data from our research conducted in the Brazilian Cerrado. This includes estimations of the aboveground biomass, belowground biomass and the biomass loss by fires. This is the first study to estimate total ecosystem biomass. This includes both the aboveground and belowground (root) biomass. Root biomass has not been measured in the Brazilian Cerrado prior to this study. Given its significant contribution to plant biomass, this was suprising. The significance of these measurements included the quantification of these sites as Global C Pools and their potential loss when these sites are converted to pasture or cropland.

II. Dynamics associated with total aboveground biomass, C, nutrient pools, and biomass burning of primary forest and pasture in Rondônia, Brazil during SCAR-B

V. Publications

Castro, E.A. and J. B. Kauffman. 1998. Ecosystem structure in the Brazilian Cerrado: A vegetation gradient of aboveground biomass, root mass and consumption by fire. J. Tropical Ecology (14:263-283).

Kauffman, J.B., D.L. Cummings, and D.E. Ward. 1998. Fire in the Brazilian Amazon: 2. Biomass, nutrient pools and losses in cattle pastures. Oecologia (113:415-427).

Kauffman, J.B., L.S. Guild, D.L. Cummings, E.A. Castro, L. Ellingson, R. Babbitt, and D.E. Ward. 1996. Total aboveground biomass, elemental pools, and combustion factors of fires sampled during the SCAR-B Experiment. SCAR-B *Proceedings,* V.W.J.H. Kirchhoff, Ed. Transtec Editorial, São José dos Campos, São Paulo. Pp. 85-88.

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Guild, L. S, J.B. Kauffman, L.J. Ellingson, D.L. Cummings, E.A. Castro, R.E. Babbitt, and D.E Ward. 1998. Dynamics associated with total aboveground biomass, C, nutrient pools and biomass burning of primary forest and pasture in Rondonia during SCAR-B. J. Geophysical Research (In press).

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Cummings, D.L., J. B. Kauffman, D.A. Perry, and R.F. Hughes. 1998. Aboveground biomass and structure of Amazonian rainforest in Northern Rondonia, Brazil. Ecological Applications (submitted).

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Hughes, R.F. and J. B. Kauffman 1998. Losses of aboveground biomass, C, N, and S pools associated with land use change in the Brazilian Amazon. Abstracts Ecol Soc Amer. Annual meeting Baltimore, MD.

Kauffman et al. 1997 Uncertainties in the estimation of biomass and deforestation of Amazon tropical forests Bull. Ecol. Soc. Amer.